PWA FR-1890
30 DEC 1966

RL10A-3-3 ROCKET ENGINE OXIDIZER PUMP DEVELOPMENT PROGRAM

Prepared Under NASA
Contract NAS8-15494
August 1965 to June 1966

Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION
FLORIDA RESEARCH AND DEVELOPMENT CENTER

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E. Zeliznak, Lewis monitor

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FOREWORD

The program discussed herein was initiated to develop an RL10A-3-3 rocket engine oxidizer pump configuration eliminating metal-to-metal rub of the inducer on the housings during all normal engine operation, without adversely affecting the overall pump performance. Although no difficulties were encountered from this rubbing during the engine and component testing with this design, experience on oxidizer pumps in other engines suggested that metal-to-metal rub was undesirable. Therefore a program was initiated to develop a configuration with no metal-to-metal rub.

This report presents the results of this development program conducted on the RL10A-3-3 engine oxidizer pump under NASA Contract NAS8-15494 for the period August 1965 to June 1966.

ABSTRACT

This report presents the results of the development program conducted on the RL10A-3-3 engine oxidizer pump under NASA Contract NAS8-15494 for the period August 1965 to June 1966.

The objectives were to:

1. Develop an oxidizer pump configuration to eliminate inducer-to-housing metal-to-metal rub without adversely affecting pump performance.
2. Determine the cause of the oxidizer pump test rig fires encountered during investigative testing directed toward the requirements of objective 1.

The program consisted of:

1. Oxidizer pump rig tests with increased inducer-to-housing clearances, a carbon insert rub ring, and intentionally heavy inducer-to-housing rubs
2. Engine tests with increased inducer-to-housing clearances and with a carbon insert rub ring
3. Design analysis
4. Pump shaft and housing static deflection tests
5. Rub tests in liquid oxygen of the materials used in the oxidizer pump.

The results were:

1. A carbon insert was added to the inducer housing bore for a labyrinth seal rub ring. The inducer blade-to-housing clearance was increased on the unshrouded portion of the inducer. This has eliminated the inducer-to-housing metal-to-metal rub on all engine and component testing conducted to date. Pump performance was not adversely affected by these changes.

2. The probable cause of the oxidizer pump test rig fires encountered during this program was a rub between the impeller front meridional contour and the housing. Operating conditions in the experimental test rig and the test configuration during which fire occurred, were not representative of engine conditions and no fires have occurred during RL10A-3-3 engine testing in over 1800 firings. However, the pump rig test indicated a potential problem and the impeller-to-housing clearance was increased for added margin in the RL10A-3-3 production engines.

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ILLUSTRATIONS (Continued)

SECTION I
INTRODUCTION

The RL10A-3-3 rocket engine is a regeneratively cooled, turbopump-fed engine with a single chamber and a rated thrust at altitude of 15,000 lb, and a nominal specific impulse of 444 sec. Propellants are liquid oxygen and liquid hydrogen injected at a nominal oxidizer-to-fuel mixture ratio of 5.0:1. Rated engine thrust is achieved at a nominal design chamber pressure of 400 psia with a nozzle area ratio of 57:1.

The initial RL10A-3-3 rocket engine oxidizer pump design permitted metal-to-metal rub of the inducer labyrinth seal on the bore of the inducer housing. Although no difficulties were encountered from this rubbing during the engine and component test program with this design, experience on oxidizer pumps in other rocket engines suggested that the metal-to-metal rub was undesirable; therefore, a program was initiated to develop a configuration with no metal-to-metal rub. The objectives were to:

1. Develop an oxidizer pump configuration to eliminate inducer-to-housing metal-to-metal rub without adversely affecting pump performance
2. Determine the cause of the oxidizer pump test rig fires encountered during investigative testing directed toward the requirements of objective 1.

This report presents the results of the development program conducted on the RL10A-3-3 engine oxidizer pump under NASA Contract NAS8-15494 for the period August 1965 to June 1966.

The RL10A-3-3 oxidizer pump was redesigned from the RL10A-3-1 model pump to accommodate the revised engine requirement of increased chamber pressure and reduced pump NPSH requirement. The design requirement was to deliver liquid oxygen at a nominal flow rate of 185 gpm, with a pressure rise of 514 psi at a speed of 12,000 rpm and inlet NPSP of 8 psid or less. Significant changes from the RL10A-3-1 pump were:

1. The impeller diameter was increased from 3.90 to 4.20 in.
2. The impeller shroud front vanes were removed
3. The forward impeller-to-housing clearance was reduced

4. The inducer diamter was increased from 1.93 to 2.26 in.
5. The forward portion of the inducer blading was unshrouded
6. The abraidable carbon rub ring was removed.

A comparison of the design differences between the RL10A-3-1 and the RL10A-3-3 oxidizer pump is shown in figure I-1.

Inducer seal clearances were set as low as possible for optimum pump performance in the RL10A-3-3 oxidizer pump design, and rubbing between the stainless steel inducer labyrinth seals and the aluminum inducer housing was a normal occurrence. In previous engine models, the RL10A-3 and RL10A-3-1, the oxidizer pump design permitted the inducer seals to rub against a carbon liner inserted into the inducer housing. This design was successful, and accumulated more than 250 hours of engine testing with no operational problems. However, the RL10A-3-3 model oxidizer pump was redesigned for improved pump performance, simplification, and convertibility to fluorine operation. This design did not have the carbon insert since carbon material is not fluorine compatible.

The decision to allow metal-to-metal rubbing in the inducer seal areas was supported by favorable results from rub tests in liquid oxygen conducted on a specially constructed test rig and oxidizer pump rig tests specifically directed to determine inducer-to-housing rubbing compatibility. The rub test program on the special rub rig is described in attached Appendix A. The RL10A-3-3 development engines have accumulated more than 53 hours of test time, and 140 hours of oxidizer pump rig testing with this configuration have been completed with no detrimental or hazardous pump operation from the inducer-to-housing rub. Inducer-to-housing rubbing was experienced during the major portion of this testing. A typical inducer housing showing the inducer seal and blade rubs is shown in figure I-2.

Although RL10 experience has been satisfactory, oxidizer pump failures resulting in fires have occurred in other pump designs. The failures, attributed to various causes, were commonly associated with a metal-to-metal rub in the pump. From this experience, it was believed possible that a fire could ultimately result from the conditions existing within the RL10 oxidizer pump. Elimination of the metal-to-metal rubs was considered desirable for improved reliability.

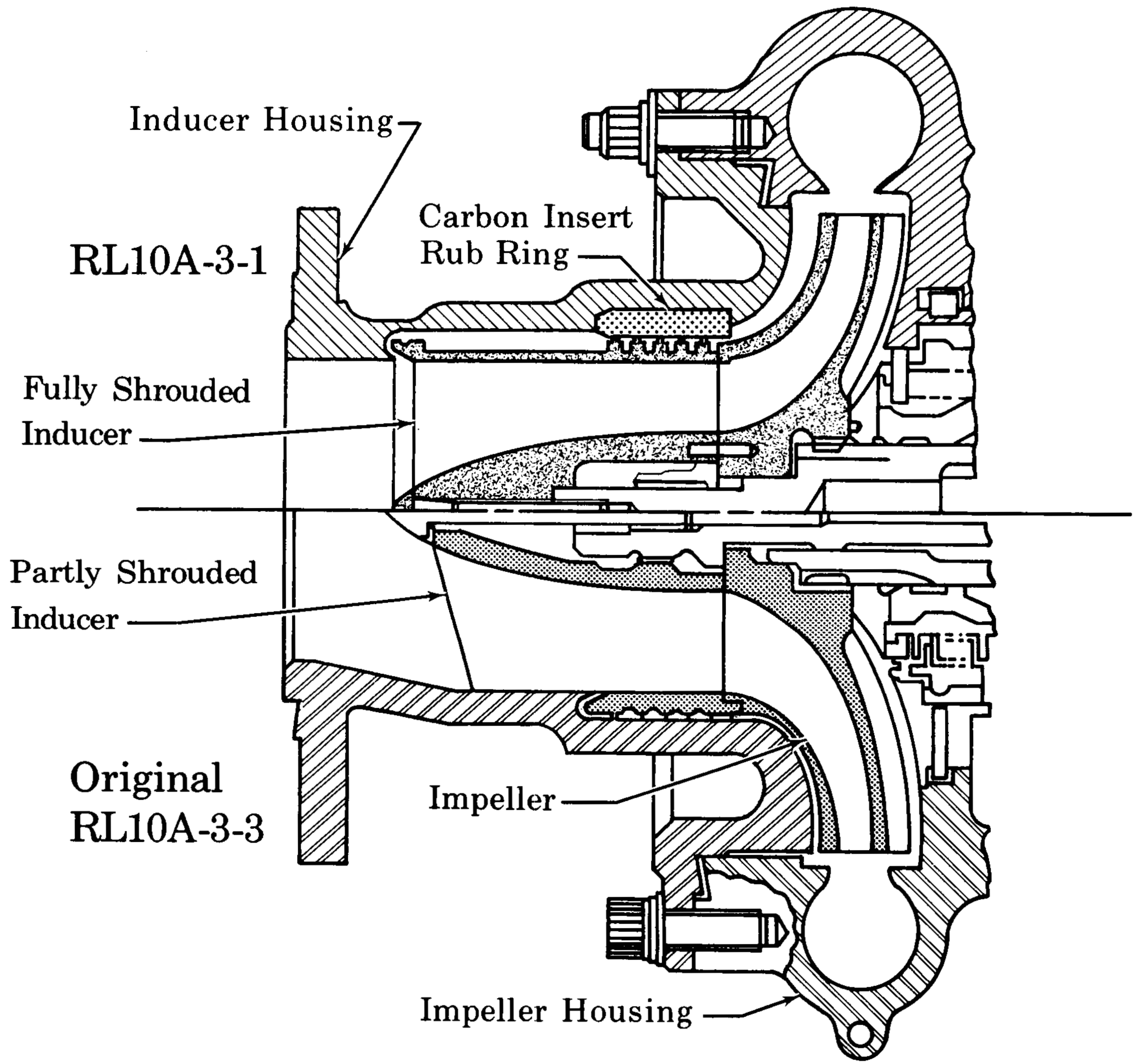

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Figure I-1. RL10 Oxidizer Pump Comparison

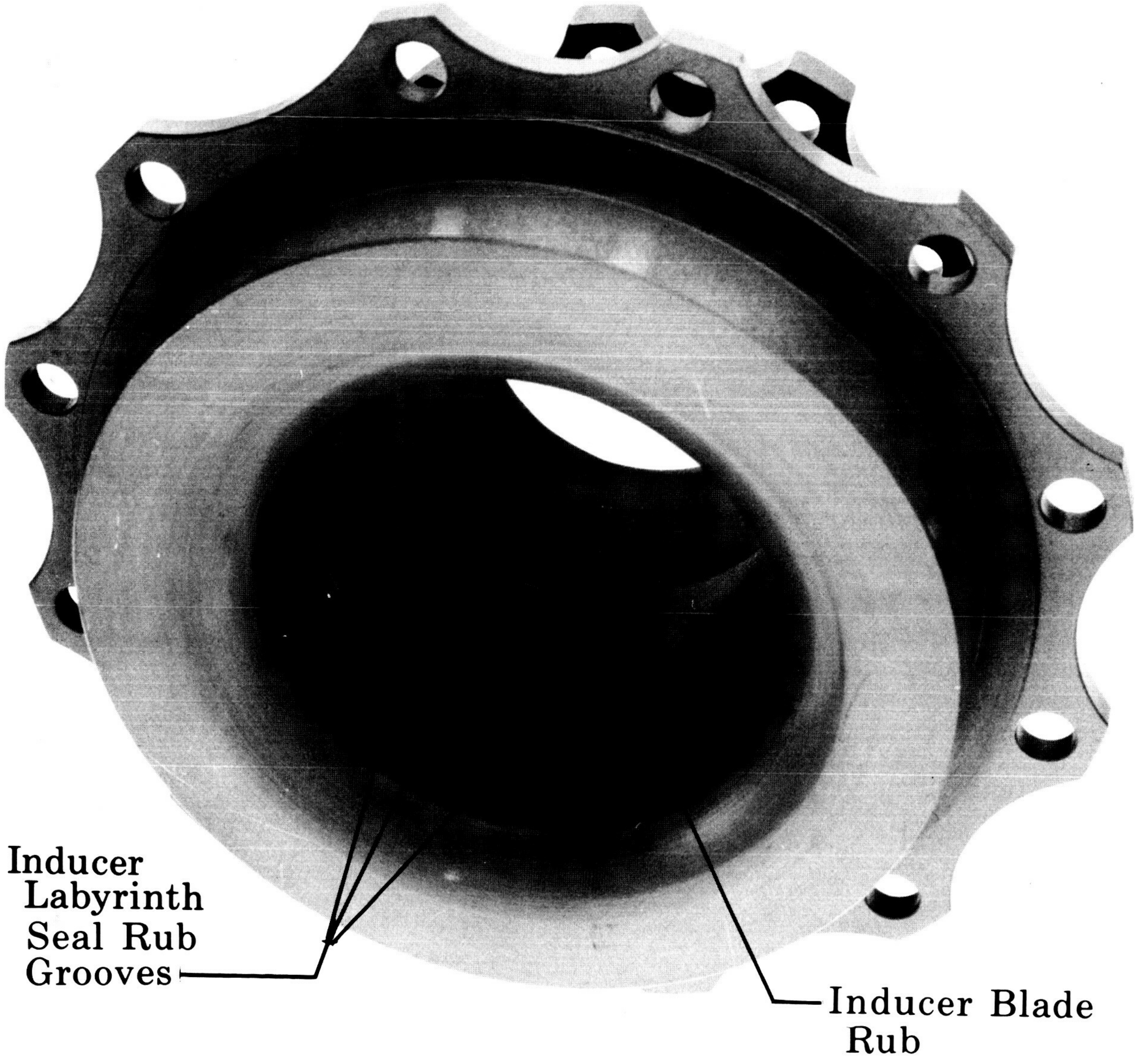

Figure I-2. RL10A-3-3 Oxidizer Pump Inducer Housing FD 18340

The actual NPSH requirement for the RL10A-3-3 oxidizer pump was lower than the minimum engine performance specification requirements. Therefore, increasing the inducer housing clearances at the expense of raising the NPSH requirements nearer the engine specification limits was considered a prime approach to eliminate the metal-to-metal inducer rubs. This was the initial plan for the program.

During this clearance change program, two fires occurred on experimental oxidizer pump test rigs. As a result, a separate test program was conducted to determine the origin of these fires. Results of this program showed that with increased inducer-to-housing clearance, an increased diameter impeller, and pump operation in deep cavitation, shaft and housing deflections large enough to permit the front side of the pump impeller to rub against the inducer housing can occur, and that such rubbing can result in a fire. A fire was initiated during a special test in which the impeller front side-to-housing clearance was set at a reduced value (outside drawing tolerances) to permit rubbing to occur. Fires could not be started from excessive inducer labyrinth seal or blade rubs.

An inducer and inducer housing design was established that satisfied the original program objectives with no loss in pump performance. This design incorporated a carbon insert in the inducer housing to provide an abradable rub surface for the inducer labyrinth seals. The impeller front side-to-housing clearance was increased to provide additional impeller-to-housing clearance margin. Also, the inducer blade-to-housing clearance and the inducer shroud-to-housing axial clearance were increased.

SECTION II
TECHNICAL DISCUSSION

A. DESCRIPTION OF TEST EQUIPMENT

All testing was performed on oxidizer pump test stand B-17. This test stand, shown in figure II-1, consisted of an electric drive motor with a reduction gearbox and dynamic drive connected, through a torque measuring device, directly to the oxidizer pump shaft. The pumped fluid, liquid oxygen or liquid nitrogen, was supplied to the rig from an insulated storage tank. A boost pump upstream of the test pump inlet provides for ciculating liquid from the storage tank through the pump and back to the tank for cooling the rig and stand system and also provides the selected oxidizer pump inlet pressure. The oxidizer pump discharge flow was returned to the propellant supply tank. The oxidizer pump speed, flow, and inlet and discharge conditions were all manually controlled. A schematic of this system is shown in figure II-2.

The standard test oxidizer pumps were RL10A-3-3 parts list pumps adapted to the test stand drive system by replacement of the oxidizer elbow housing with a test adapter housing. Figure II-3 shows a cross-sectional view of the RL10A-3-3 oxidizer pump. A view of a pump mounted in the test stand is shown in figure II-4. In addition, an oxidizer pump rig, B71C005, was specifically designed to provide controlled radial movement of the oxidizer pump shaft during pump operation to force heavy inducer labyrinth seal-to-housing rubs. This was accomplished by containing the thrust bearing support in a movable yoke. A drawing of this rig is presented in figure II-5. The yoke position and movement were controlled by a shaft driven by an air cylinder with appropriate stops, as seen in figure II-6. Radial movement of the yoke and bearing forced the inducer into heavy rubbing on the housing bore. Radial loads up to 1500 lb could be applied to the bearing support with the air cylinder. Figure II-7 shows a typical pump installation in the cryogenic test stand.

Two separate programs were actually conducted; therefore, the technical discussion will be divided into two parts, each part describing one of the stated objectives.

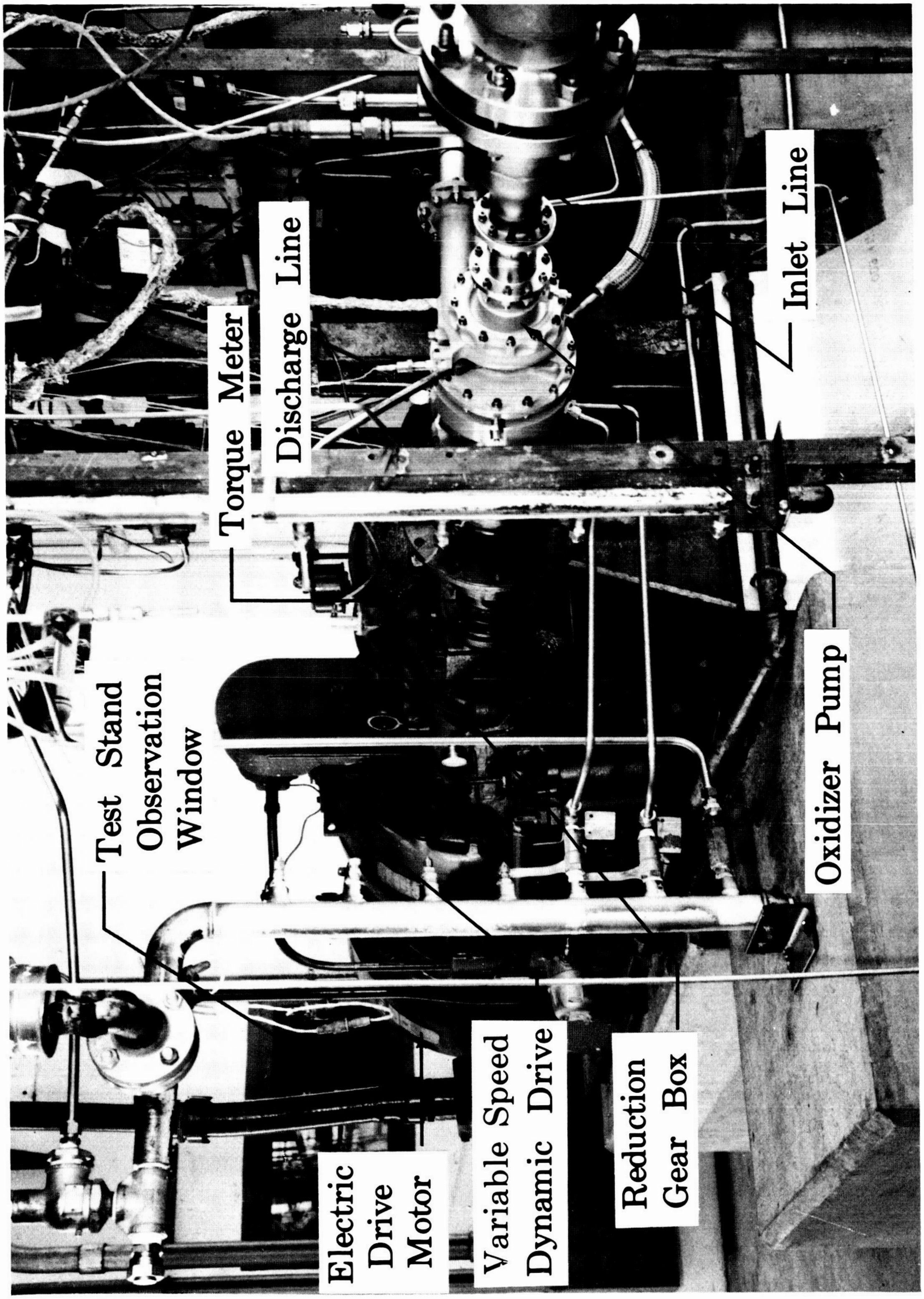

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Figure II-1. B-17 Rig Test Stand

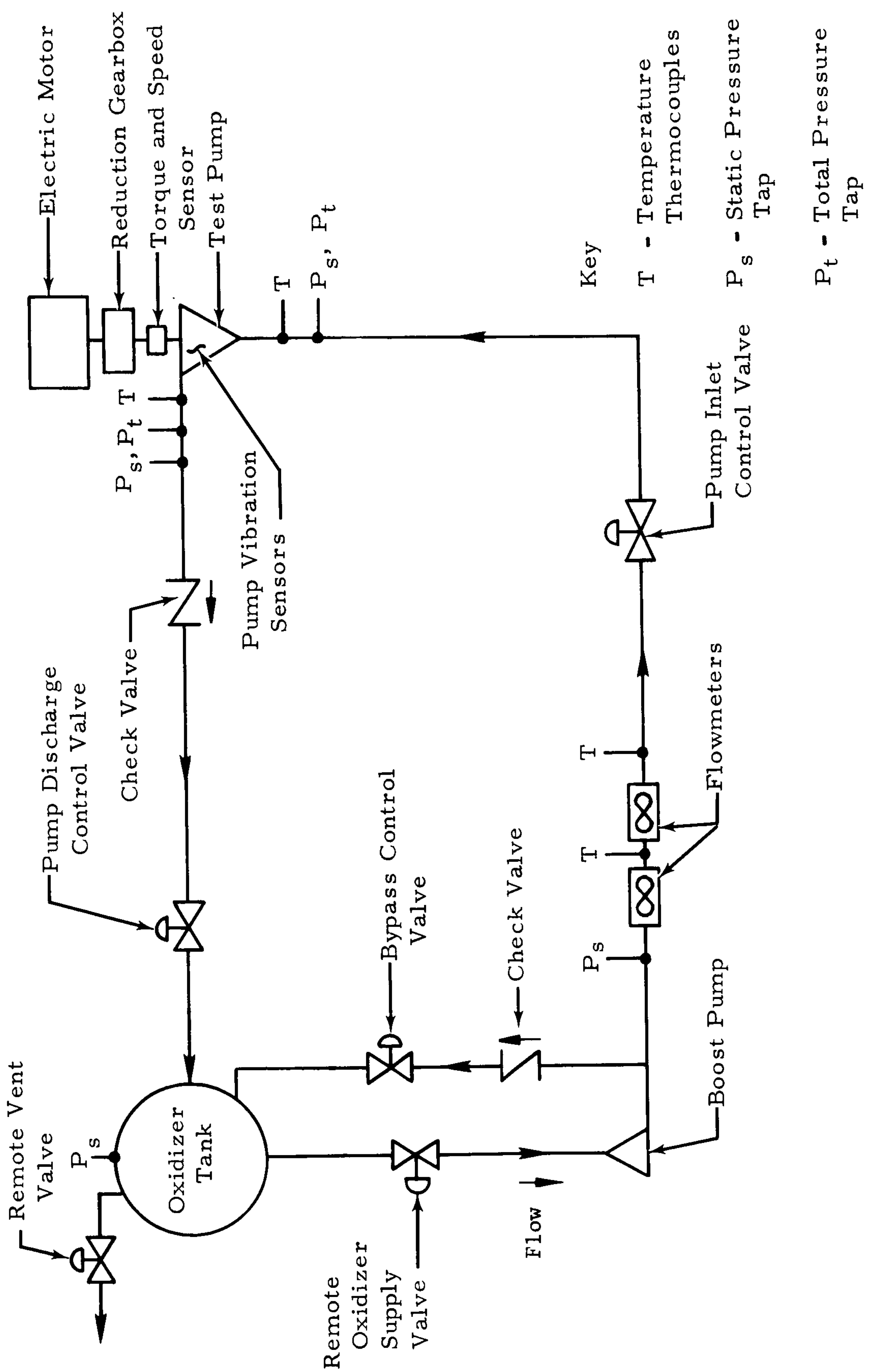

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Figure II-2. Schematic of B-17 Rig Test Stand

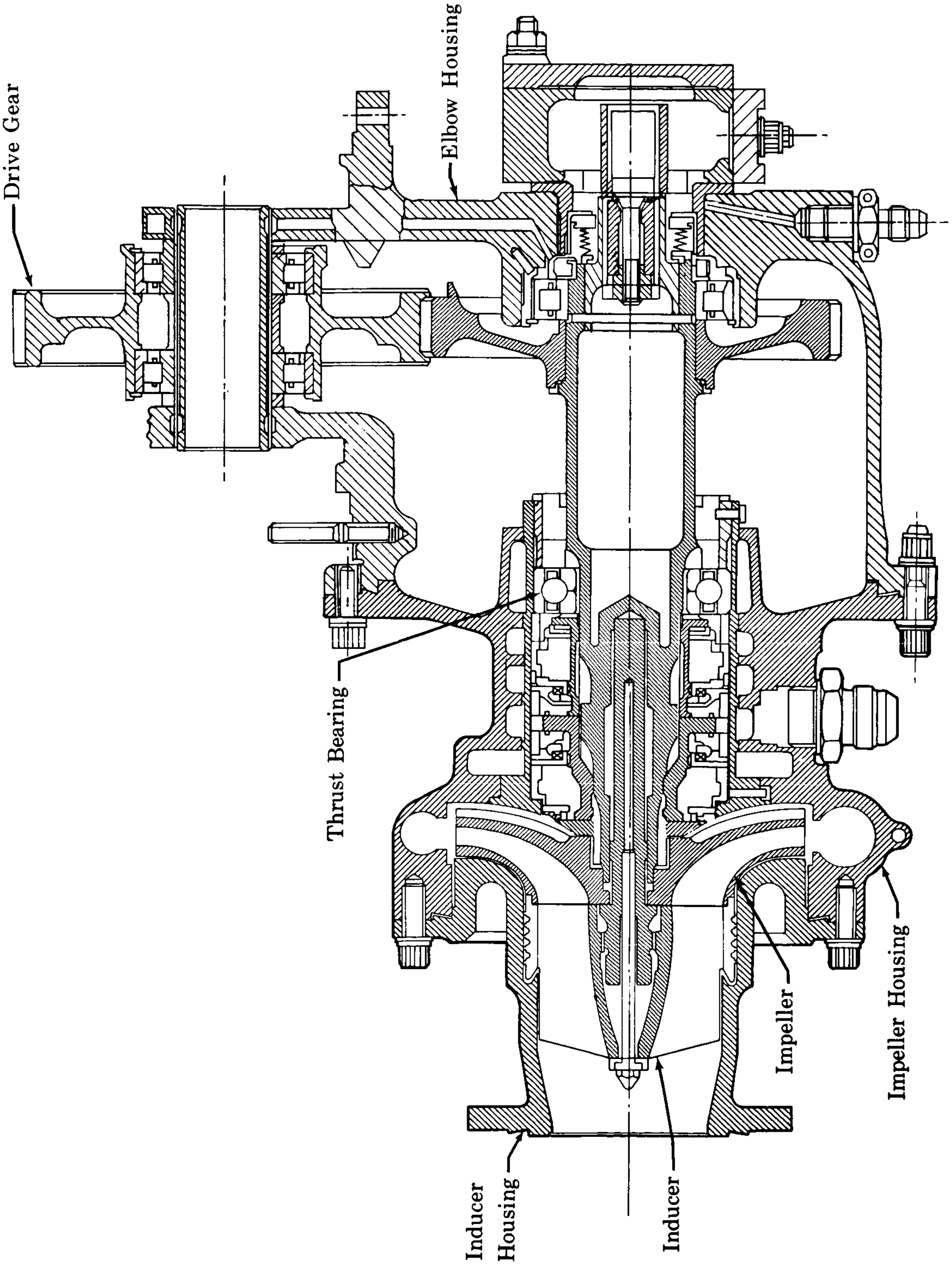

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Figure II-3. Original RL10A-3-3 Oxidizer Pump

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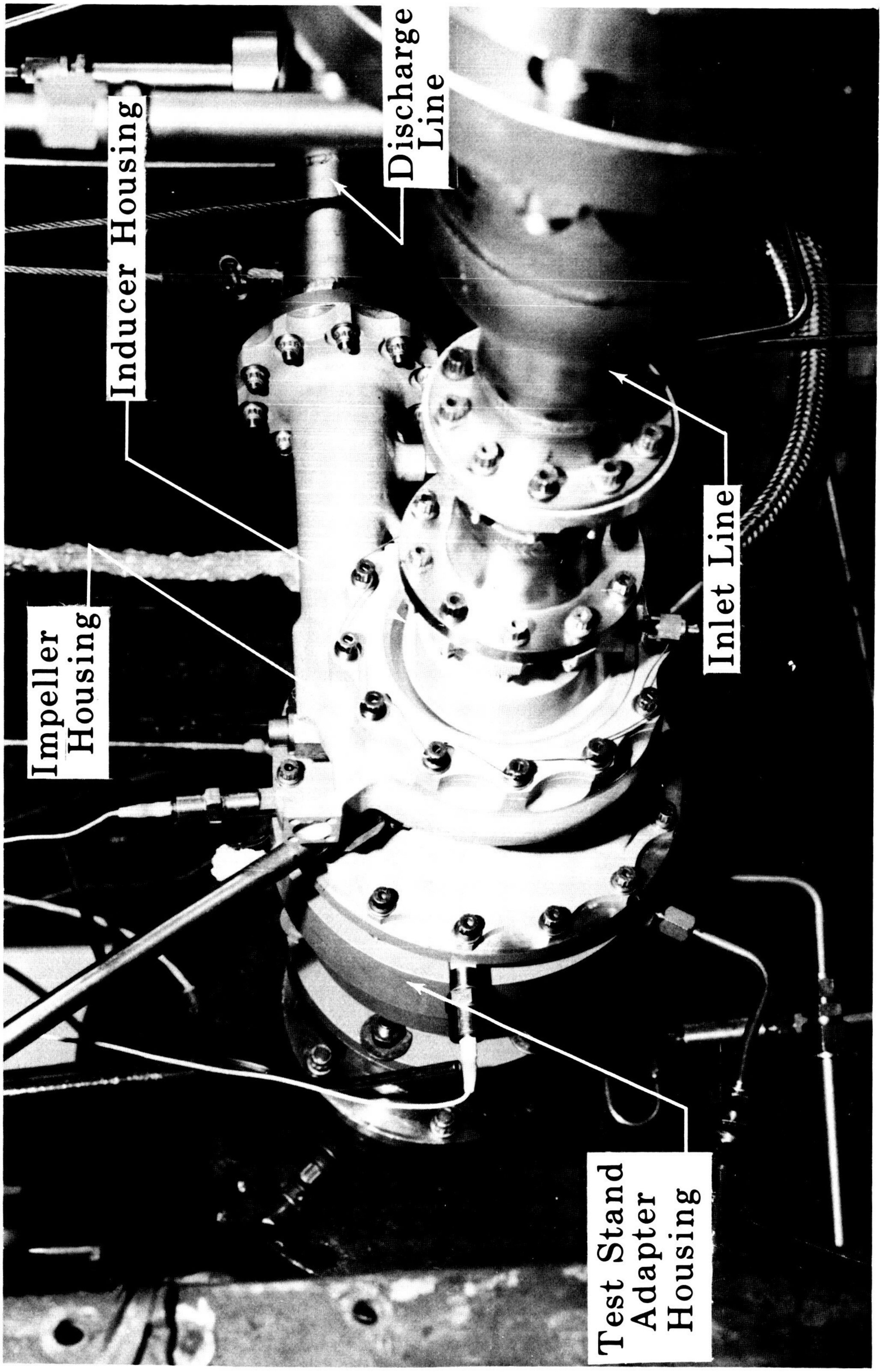


Figure II-4. RL10 Oxidizer Pump Mounted in Test Stand

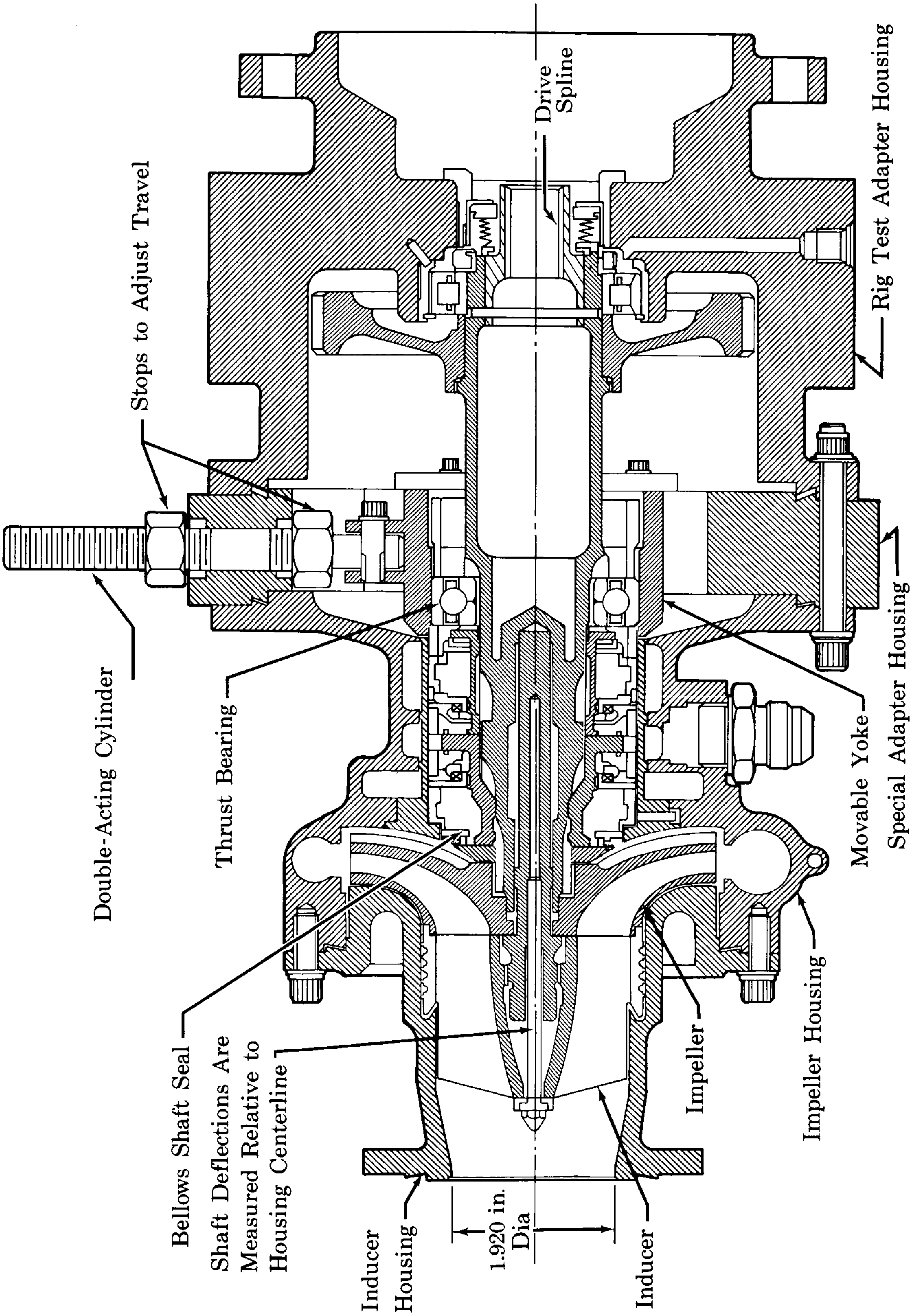


Figure II-5. Oxidizer Pump Shaft Deflection Rig

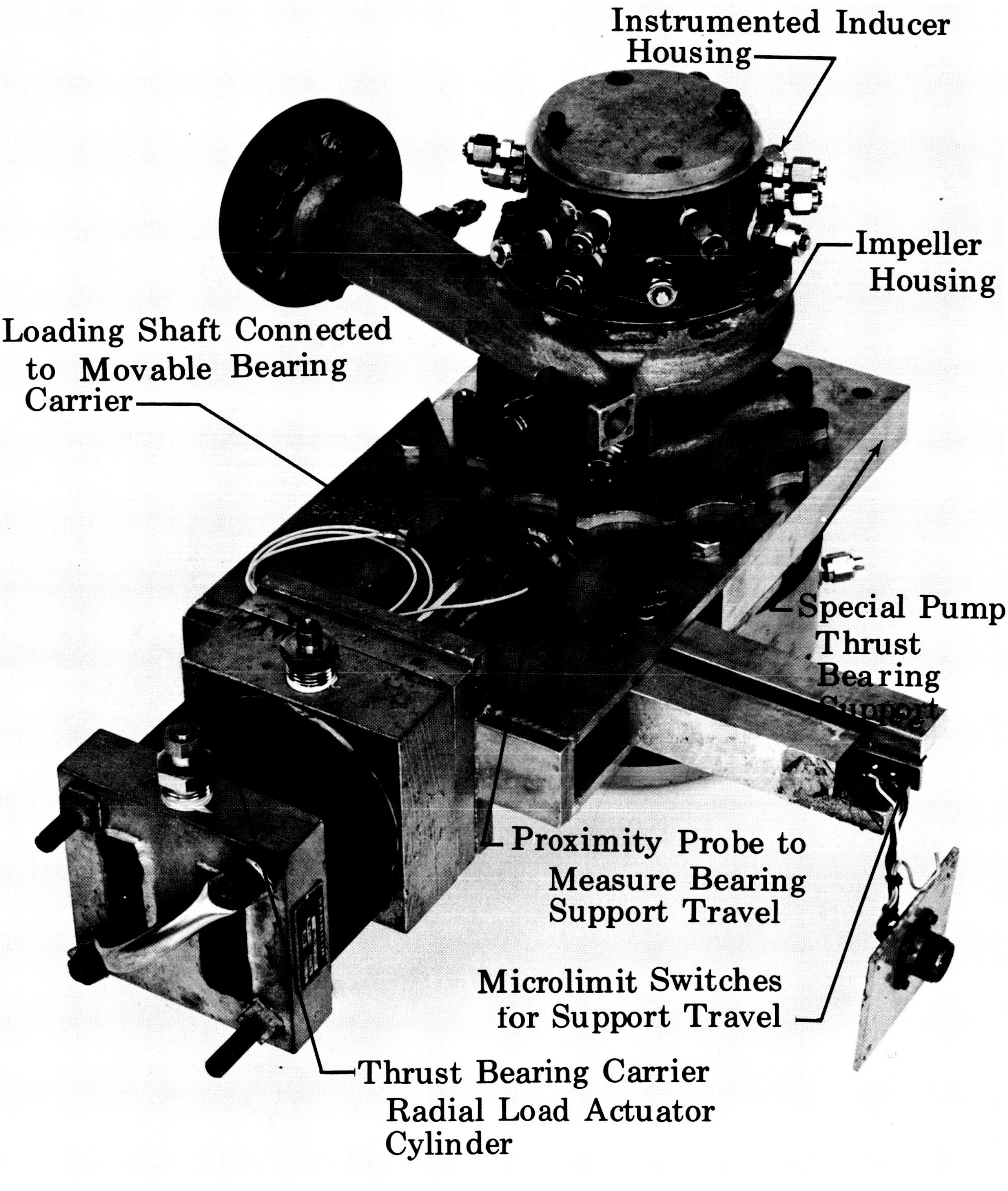


Figure II-6. RL10 Oxidizer Pump Shaft Deflection Rig

FD 18360

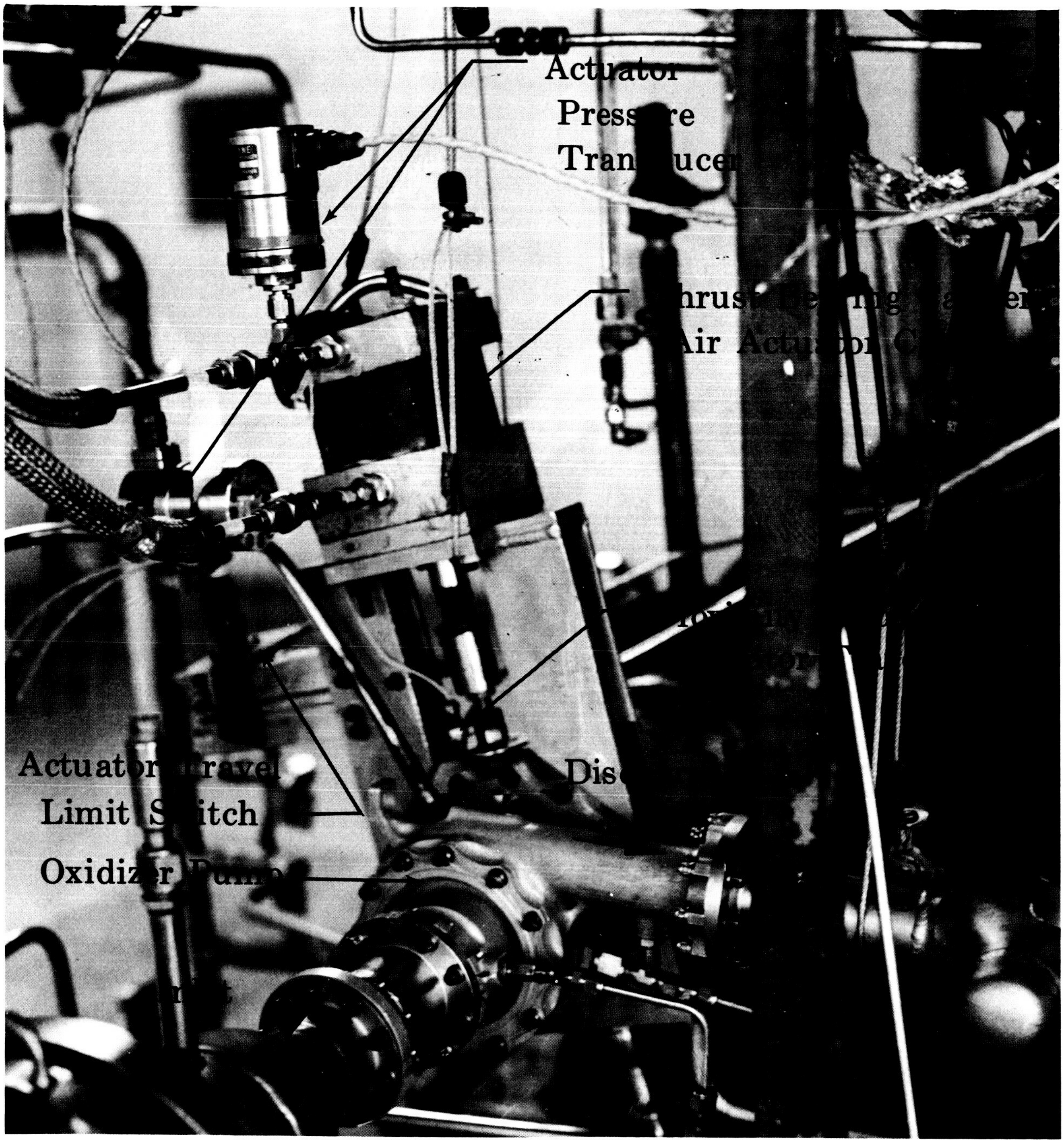


Figure II-7. RL10 Oxidizer Pump Rig B71C005 Mounted in Test Stand FD 18365

B. OXIDIZER PUMP INDUCER CLEARANCE PROGRAM

This program consisted of a series of oxidizer pump tests to determine the effect on pump head rise and inlet net positive suction pressure (NPSP) of increasing the inducer labyrinth seal-to-housing and blade-to-housing clearances, and to establish the minimum clearances required to eliminate rubbing.

The minimum pump NPSP requirement, by definition, is the minimum pump inlet pressure above the vapor pressure of the pumped fluid at which the pump pressure rise is no less than 97% of the value at high NPSP levels. In this report a decrease in head rise at fixed speed and flow will be termed "cavitation." Thus the minimum NPSP is determined at the point that the pump is 3% in cavitation or 3% below the normal head rise for the particular speed and flow conditions. The RL10A-3-3 oxidizer pump minimum NPSP requirement, established from both rig and engine data, at a speed of 11,700 rpm and 192 gpm flow, is 3.6 psid, as shown in figure II-8, which is considerably below the engine specification minimum of 8 psid. This is the nominal speed and flow rate during engine operation at a mixture ratio of 5.6. During the previous development programs, tests were conducted at pump speeds of 11,000 and 12,000 rpm, and at flow rates of 175, 185, and 192 gpm, covering the engine requirements. For the subject program one speed and one flow point was considered sufficient to determine the comparative performance of a modification. The selected comparison condition was 11,000 rpm and 185 gpm. A tabulation of the tests performed in this and the fire investigation program are summarized in table 1.

The RL10A-3-3 oxidizer pump parts list inducer-to-housing labyrinth seal and blade nominal diametrical clearances were 0.010 and 0.040 in., respectively. (Throughout this report all clearances will be diametrical unless otherwise specified.) For the first three tests the labyrinth seal clearances were opened to 0.020, 0.050, and 0.080 in., respectively, and the blade clearance was held constant at 0.040 in. (rig B71C003, tests 1, 2, and 3 in table 1). The test results, presented in figure II-9, show that the NPSP requirement was significantly increased with increased clearance. The NPSP specification limit of 8 psid was exceeded above

0.035 in. inducer labyrinth seal clearance. Although some seal rubbing was still evident at clearances greater than 0.035 in., the rig program was continued to determine if rub conditions in the rig were the same as in the engine and to define a configuration for engine test.

Since inducer blade rubbing was also observed, the blade clearance was increased to 0.050 in. for the next test. For this test, rig B71C003, test 4, the 0.050-in. blade clearance was combined with a labyrinth seal clearance of 0.030 in. to maintain NPSP specification limit. The NPSP requirement, instead of slightly increasing as expected, was reduced to 2.5 psid, as shown in test 4, figure II-10. The test was repeated, rig B71C003, tests 5 and 6, except the labyrinth seal clearance was increased to 0.040 in. This change in the seal clearance produced an effect that paralleled the original labyrinth seal clearance curve. Further testing with blade clearances of 0.060 and 0.070 in., rig B71C003, tests 7 through 9, figure II-10, verified that the NPSP requirement was sensitive to the blade-inducer clearance match. This characteristic of the pump NPSP performance was attributed to the increase in inducer leakage past the labyrinth seals that changed the pre-swirl forward of the inducer and improved the fluid incidence angle into the inducer blading. The improved NPSP effect on the pump reached an optimum between a blade clearance of 0.060 and 0.070 in.

Compromises between inducer labyrinth seal and blade clearances were investigated. A minimum inducer seal and blade clearance of 0.040 and 0.050 in., respectively, was necessary to maintain an adequate NPSP requirement. However, test results showed that the 0.040-in. labyrinth seal clearance would not eliminate the metal-to-metal rubs. The inducer seal rub with the increased inducer clearance was as severe as with the original close clearance. The heaviest contact area was always oriented in an arc nominally ± 60 degrees opposite the cutwater in the impeller housing, although 360-degree rubs in the inducer housing were at times observed. The orientation of the contact area was consistent with the unsymmetrical loading of the inducer and impeller caused by the varying pressure levels existing around the impeller periphery. The pump shaft was deflecting radially, and as the seal clearances were increased the pump shaft deflected further. The labyrinth seals rubbing against the inducer housing had been acting as a bearing and prevented further shaft deflection.

DF 50258

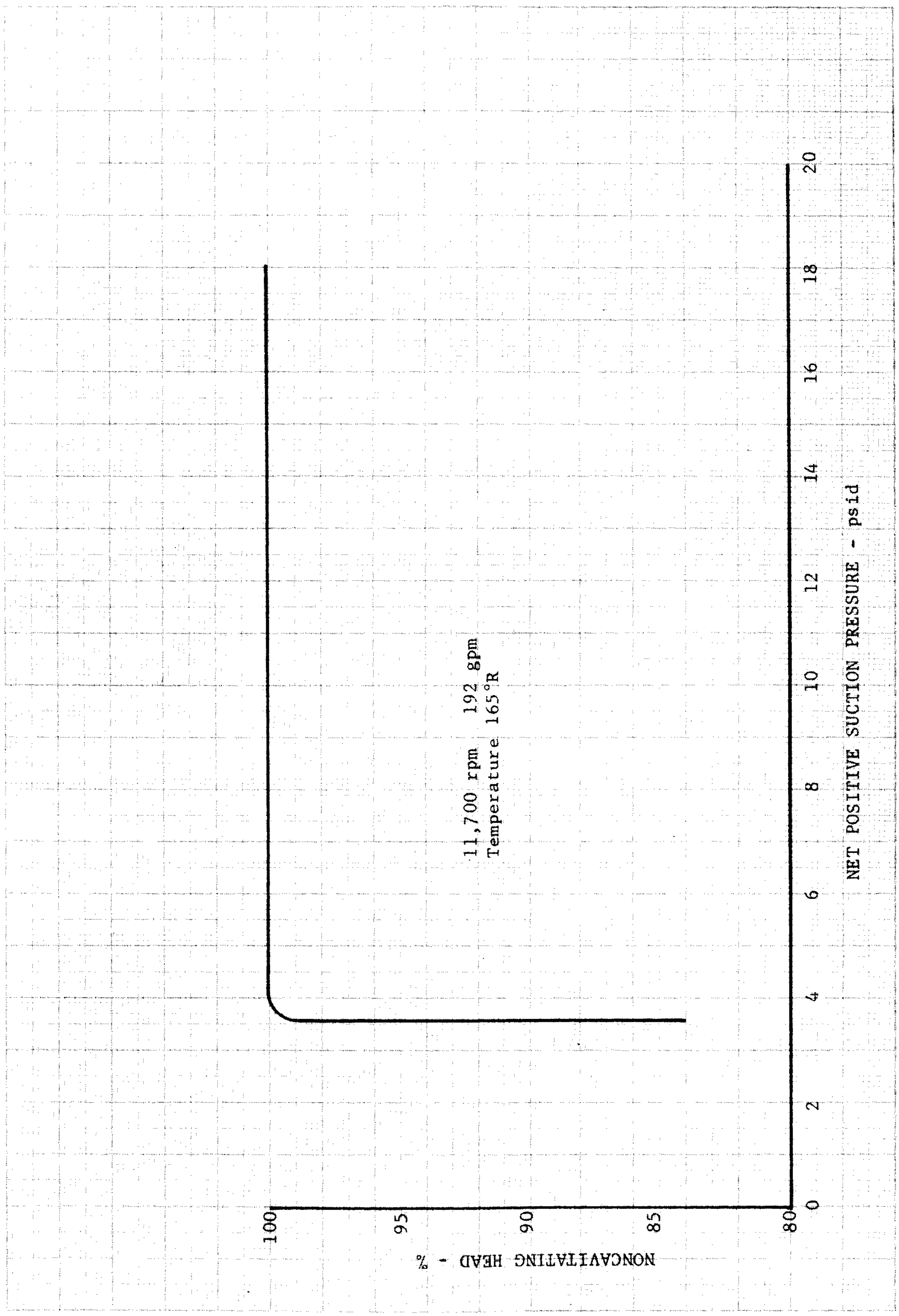


Figure **II-8.** RL10A-3-3 Oxidizer Pump NPSP Performance

Table II-1. RL10A-3-3 Oxidizer Pump Inducer Clearance Test Summary

Test Rig No.	Test	Test Date	Test Fluid	Inducer Diametrical Clearances, in. Blade Pre-Test	Blade Post-Test	Labyrinth Seals Pre-Test	Labyrinth Seals Post-Test	Impeller Clearances, in. Axial Fore	Axial Aft	Diametrical	Remarks
B71C003	1	8/23/65	LO_2	0.040	—	0.020	—	0.070	0.050	0.180	2.4 NPSP required at 12,000 rpm and 185 gpm.
	2	8/24/65	LO_2	0.040	—	0.050	—	0.070	0.050	0.180	11.6 NPSP required at 11,000 rpm and 185 gpm.
	3	8/26/65	LO_2	0.040	—	0.080	—	0.070	0.050	0.180	15.4 NPSP required at 11,000 rpm and 185 gpm.
	4	8/28/65	LO_2	0.050	—	0.030	—	0.070	0.050	0.180	2.5 NPSP required at 11,000 rpm and 185 gpm.
	5	9/24/65	LO_2	0.050	—	0.040	—	0.069	0.050	0.180	4.9 NPSP required at 11,000 rpm and 185 gpm.
	6	10/4/65	LO_2	0.050	—	0.040	—	0.069	0.050	0.180	5.9 NPSP required at 11,000 rpm and 185 gpm.
	7	10/15/65	LO_2	0.060	—	0.040	—	0.048	0.069	0.180	NPSP not defined.
	8	10/28/65	LO_2	0.060	—	0.040	—	0.062	0.055	0.180	5.8 NPSP required at 11,000 rpm and 185 gpm.
	9	11/12/65	LO_2	0.070	—	0.040	—	0.058	0.061	0.180	6.8 NPSP required at 11,000 rpm and 185 gpm.
	10	11/29/65	LO_2	0.050	0.050	0.040	0.040	0.059	0.061	0.180	NPSP not defined - no blade or lab seal rub.
	11	12/16/65	LO_2	0.060	—	0.040	—	0.051	0.066	0.090	5.3 NPSP required at 11,000 rpm and 185 gpm. Pump fire after 27 minutes of test duration.
	12	1/20/66	LO_2	Offset Center 0.030 max 0.020 min	—	Offset Center 0.030 max 0.005 min	—	0.062	0.054	0.090	Pump fire after 1.27 hours of test duration.
	13	2/1/66	LN_2	0.030	—	0.012	—	0.0462	0.065	0.090	Inducer blade and labyrinth seal rub.
	14	2/3/66	LN_2	—	0.067	—	0.040	No parts change from previous build.			Labyrinth seal rub groove depth in housing was 0.008-0.012 in.
	15	2/7/66	LN_2	0.068	0.088	0.040	0.049	0.0462	0.065	0.090	Same head rise as test No. 11. Blade and labyrinth seal wear.
	16	2/14/66	LN_2	0.088	0.0915	0.049	0.055	No parts change from previous build.			Same head rise as test No. 12. Blade and labyrinth seal wear.
	17	2/25/66	LO_2	0.010	0.043	0.180	0.180	0.048	0.064	0.180	Heavy inducer blade rub.
	18	3/4/66	LO_2	0.062	0.062	0.180	0.180	0.050	0.069	0.180	Slight inducer blade rub.
	19	3/5/66	LO_2	0.062	0.062	0.180	0.180	0.0887	0.033	0.180	No impeller rub with decreased aft clearance.
	20	3/10/66	LO_2	0.062	0.062	0.180	0.180	0.101	0.014	0.180	No impeller rub with decreased aft clearance.
	21	3/15/66	LO_2	0.062	—	0.180	—	0.027	0.093	0.180	Pump fire with reduced front impeller-to-housing axial clearance.
	22	3/26/66	LN_2	0.070	0.070	0.055	0.055	0.048	0.069	0.180	No impeller rub.
	23	3/26/66	LN_2	0.070	0.070	0.055	0.055	0.038	0.079	0.090	No impeller rub with slightly reduced forward impeller clearance and oversize impeller.
	24	4/26/66	LN_2	0.070	0.070	0.055	0.055	0.038	0.079	0.090	Repeat previous test at higher head rise, no impeller rub.

Table II-1. RL10A-3-3 Oxidizer Pump Inducer Clearance Test Summary (Continued)

Test Rig No.	Test	Test Date	Test Fluid	Inducer Diametrical Clearances, in. Blade Pre-Test	Blade Post-Test	Labyrinth Seals Pre-Test	Labyrinth Seals Post-Test	Impeller Clearances, in. Axial Fore	Axial Aft	Diametrical	Remarks
B71C006	1	2/16/66	LN_2	Offset Center 0.030 max 0.028 min		Offset Center 0.030 max 0.010 min		0.054	0.060	0.180	Repeated previous test.
		2/16/66	LO_2	0.050	0.0513	0.010	0.021	0.054	0.060	0.180	Maximum carbon insert groove wear was 0.0134 in.
	2	2/26/66	LO_2	0.060	0.061	0.010	0.011	0.062	0.0635	0.180	Maximum carbon groove depth of 0.0125 in. with a new carbon insert.
	3	3/3/66	LO_2	0.070	0.070	0.011	0.013	0.062	0.0635	0.180	No significant change in performance with increased inducer blade-to-housing clearance.
	4	3/12/66	LO_2	0.100	0.100	0.013	0.013	0.048	0.0695	0.180	No significant change in performance with increased inducer blade-to-housing clearance.
	5	3/21/66	LO_2	0.100	0.100	0.022	0.022	0.051	0.068	0.180	Some performance loss with additional labyrinth seal clearance.
	6	3/25/66	LO_2	0.100	0.100	0.022	0.022	0.051	0.068	0.180	Inducer labyrinth seal shroud-to-housing axial clearance increased to 0.050 in.
	7	3/29/66	LO_2	0.072	0.072	0.008	0.010	0.136	0.054	0.180	Completed 5 hours of a planned 10-hour endurance test with increased clearances and carbon liner. Groove depth 0.008 in. in carbon.
	8	3/31/66	LO_2	0.072	0.072	0.010	0.014	0.136	0.054	0.180	Completed 10-hour endurance test on inducer housing with carbon liner. Total carbon groove depth was 0.013 in.
B71C005	1	4/21/66	LN_2	0.231	0.231	0.200	0.200	0.056	0.059	0.180	Deflection rig checkout test. Experienced rub on the impeller front contour.
		4/25/66	LN_2	0.048	0.048	0.021	0.022	0.056	0.059	0.180	Impeller rub was not reproduced.
	2	4/28/66	LO_2	0.140	0.140	0.022	0.022	0.118	0.068	0.180	Could not deflect shaft due to icing of actuator shaft.
		4/29/66	LO_2	0.140	0.140	0.022	0.022	0.118	0.068	0.180	Deflected inducer 0.012 in. Wore groove in carbon insert to a depth of 0.007 in. maximum.
	3	5/27/66	LO_2	0.140	0.140	0.022	0.023	0.124	0.061	0.180	Deflected pump shaft 0.050 in. Carbon insert groove depth 0.011 in. maximum.
		6/1/66	LO_2	0.165	0.165	0.023	—	0.124	0.061	0.180	Pump shaft only partially deflected due to icing of actuator shaft. Inducer seal wear groove was 0.003 in. deep in aluminum type inducer housing.
		6/9/66	LO_2	0.165	0.165	0.023	0.024	0.124	0.061	0.180	Pump shaft deflected 0.045 in. Inducer seal wear groove depth was 0.014 in. in aluminum inducer housing.

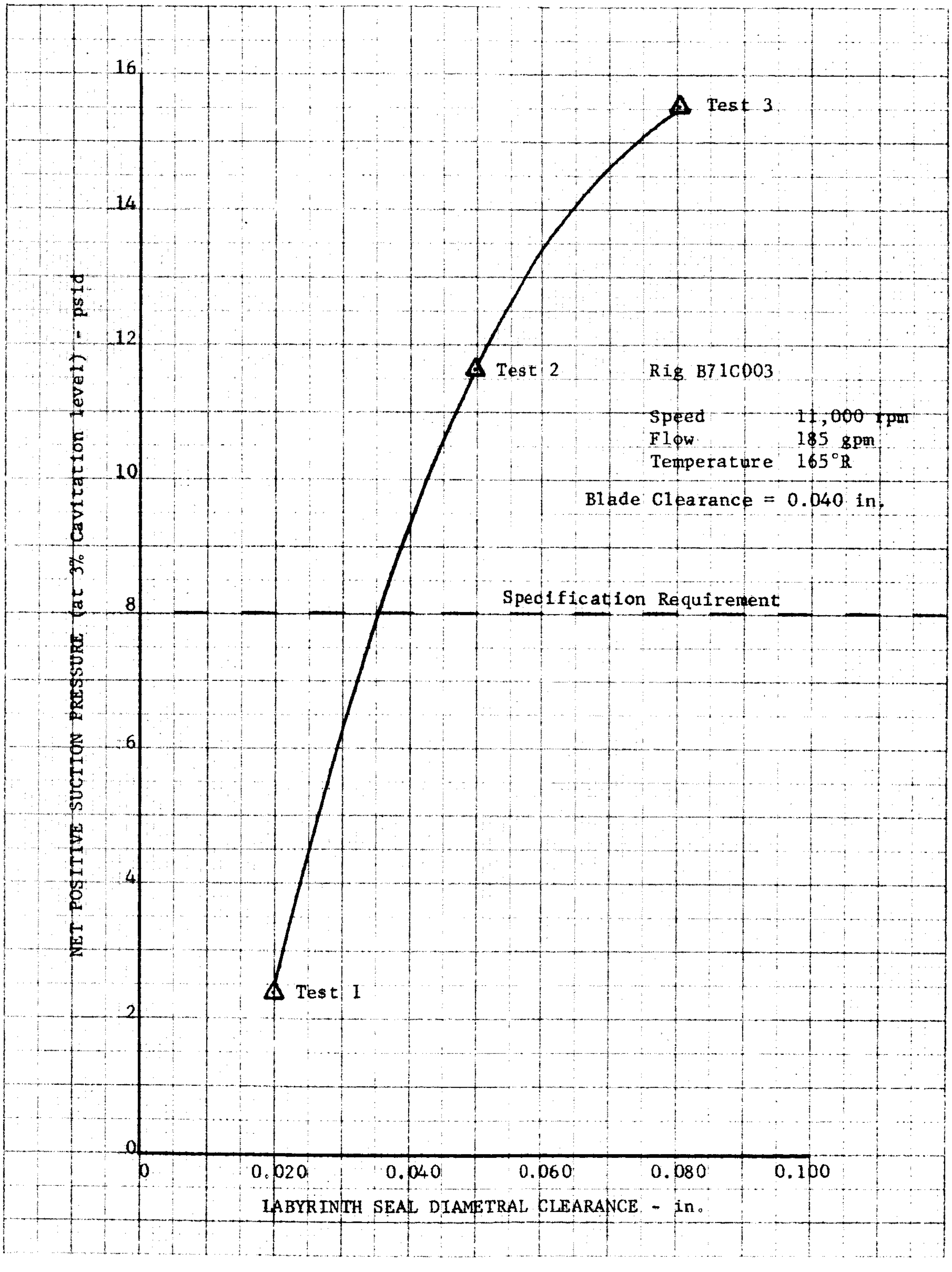


Figure II-9. RL10A-3-3 Oxidizer Pump NPSP vs Labyrinth Seal Clearance DF 50259

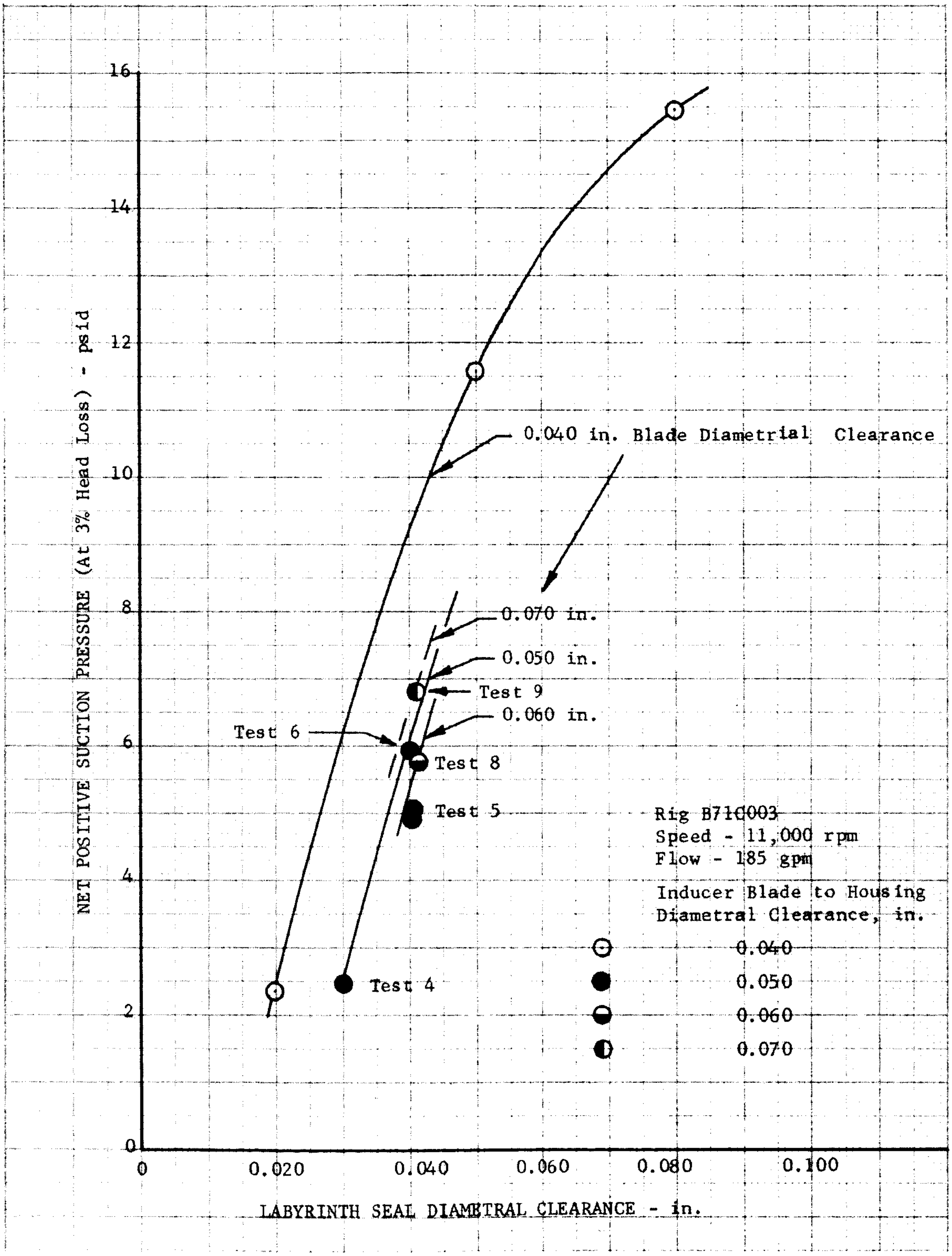


Figure II-10. RL10A-3-3 Oxidizer Pump NPSP vs Labyrinth Seal Clearance and Inducer Blade Clearance   DF 50260

The oxidizer pump head rise was also decreased approximately 2% because of the increased recirculation with increased seal clearance. With a high engine mixture ratio, the loss in the head rise was greater than tolerable for satisfactory engine operation. The oxidizer impeller diameter was therefore increased 0.10 in. to 4.30 in. for the next test increasing the head rise approximately 5%.

The planned objectives of the next pump tests, rig B71C003, tests 10, 11, and 12 (table II-1), were to determine:

1. The pump NPSP characteristics with seal and blade clearances of 0.040 and 0.050 in., respectively

2. Pump head rise with the 4.30-in. diameter impeller

3. The effect of an eccentric inducer-to-housing clearance.

The eccentric clearance was set by machining an eccentric opening in the inducer housing offset in the direction of maximum inducer rubbing. This increased the radial seal and blade clearance on one side and retained the parts list clearance on the opposite side providing the needed local clearance to compensate for the shaft deflection without losing the necessary close clearances essential for NPSP performance.

There was no blade or labyrinth seal rub on test 10 with seal- and blade-to-housing clearances of 0.040 in. and 0.050 in. respectively. Test 11 was a repeat of test 10 except that the 4.30-in. diameter impeller was installed. This test was terminated, after 27 minutes duration, by a failure resulting in a fire. The pump was operating at a speed of 11,000 rpm, flowing 185 gpm, and was approximately 12% in cavitation. This was the first series of cavitation points in this test taken to determine the minimum NPSP requirement. No abnormalities were noted before the fire was observed. General views of the failure can be seen in figures II-11, II-12, II-13, and II-14. The initial investigation concluded that the probable cause of the failure was a result of a failed front bellows seal rub plate shown in figure II-15. The rub plate was a development part made of Kentanium material being tested as a part of the shaft seal development program. This initial conclusion, however, became questionable when in test 12 of rig B71C003 a repeat failure occurred after completing 1.27 hours of testing. The Kentanium rub plate had been replaced with the parts list rub plate for this test. This second failure occurred after the third NPSP data run had been completed. The pump, recovering from a 35% cavitation point, was operating at a speed of 12,000 rpm and a flow of 185 gpm. Again no pump abnormalities were observed before this failure. General views of the failed pump are shown in figures II-16, II-17, II-18, and II-19.

With the advent of the two fires it became essential to investigate these failures before any further approaches to the inducer-to-housing metal-to-metal rub problem could be undertaken.

C. OXIDIZER PUMP FAILURE INVESTIGATION

Analysis of the failed pumps indicated that a fire could have originated in the impeller or inducer area, or possibly from a failed impeller housing cutwater. The initial investigation revealed similarities between both failures as listed below:

1. Both fires occurred while the pumps were operating in cavitation
2. Inducer-to-housing clearances were increased in both pumps
3. An increased diameter impeller was incorporated that reduced the impeller-to-housing radial clearance from 0.100 to 0.045 in.

Extensive experience has been accumulated on RL10A-3-3 oxidizer pumps running in cavitation. More than 18.6 hours of cavitating pump operation had been completed with no detrimental pump effects except for slight erosion of the impeller housing cutwater. However, oxidizer pump testing with increased inducer clearances and increased diameter impellers was limited.

An instrumented oxidizer pump was assembled to the same configuration and running clearances as the first pump that failed. Tests were conducted at conditions equivalent to those experienced by the failed pumps except that the pumped fluid was nitrogen rather than oxygen. The purposes of these tests were to determine the following:

1. The magnitude of pump discharge pressure fluctuations due to reduced impeller-to-cutwater radial clearance resulting from the large impeller, as compared to the parts list impeller
2. The location of any rubs occurring during operation in deep pump cavitation.

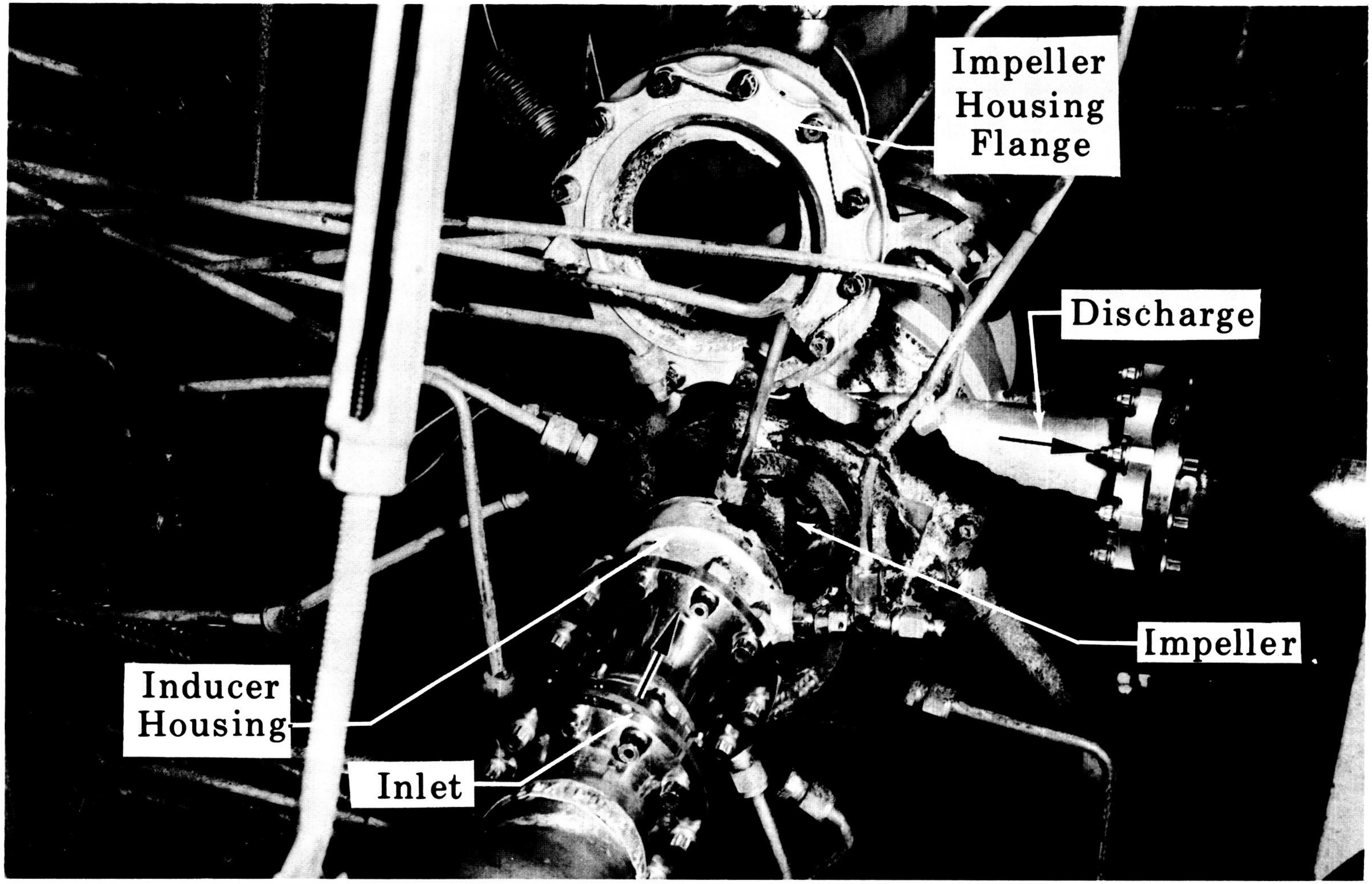


Figure II-11. RL10A-3-3 Oxidizer Pump Failure (Rig B71C003-11)

FD 18363

FD 18366

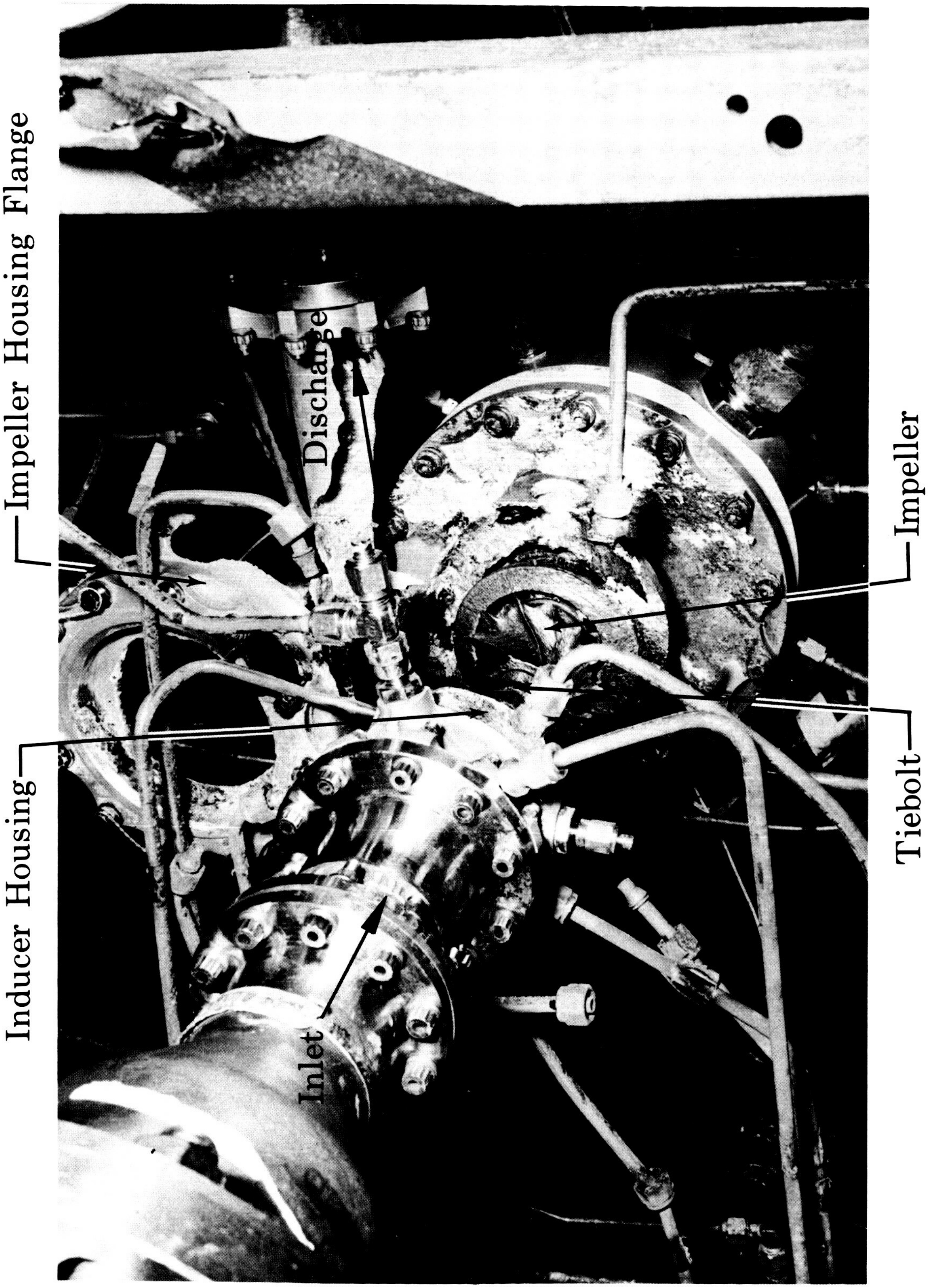


Figure II-12. RL10A-3-3 Oxidizer Pump Failure (Rig B71C003-11)

FD 18367

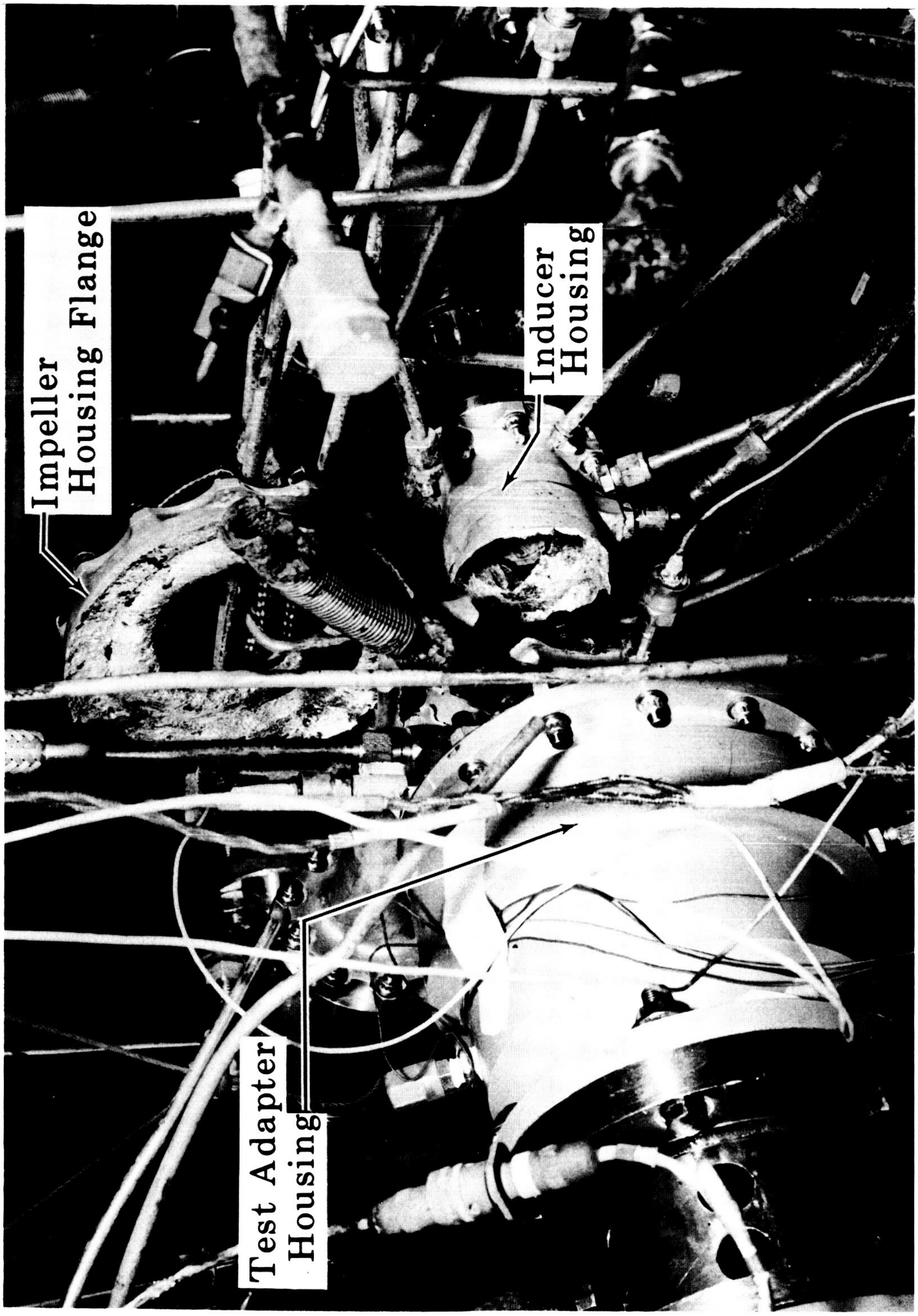
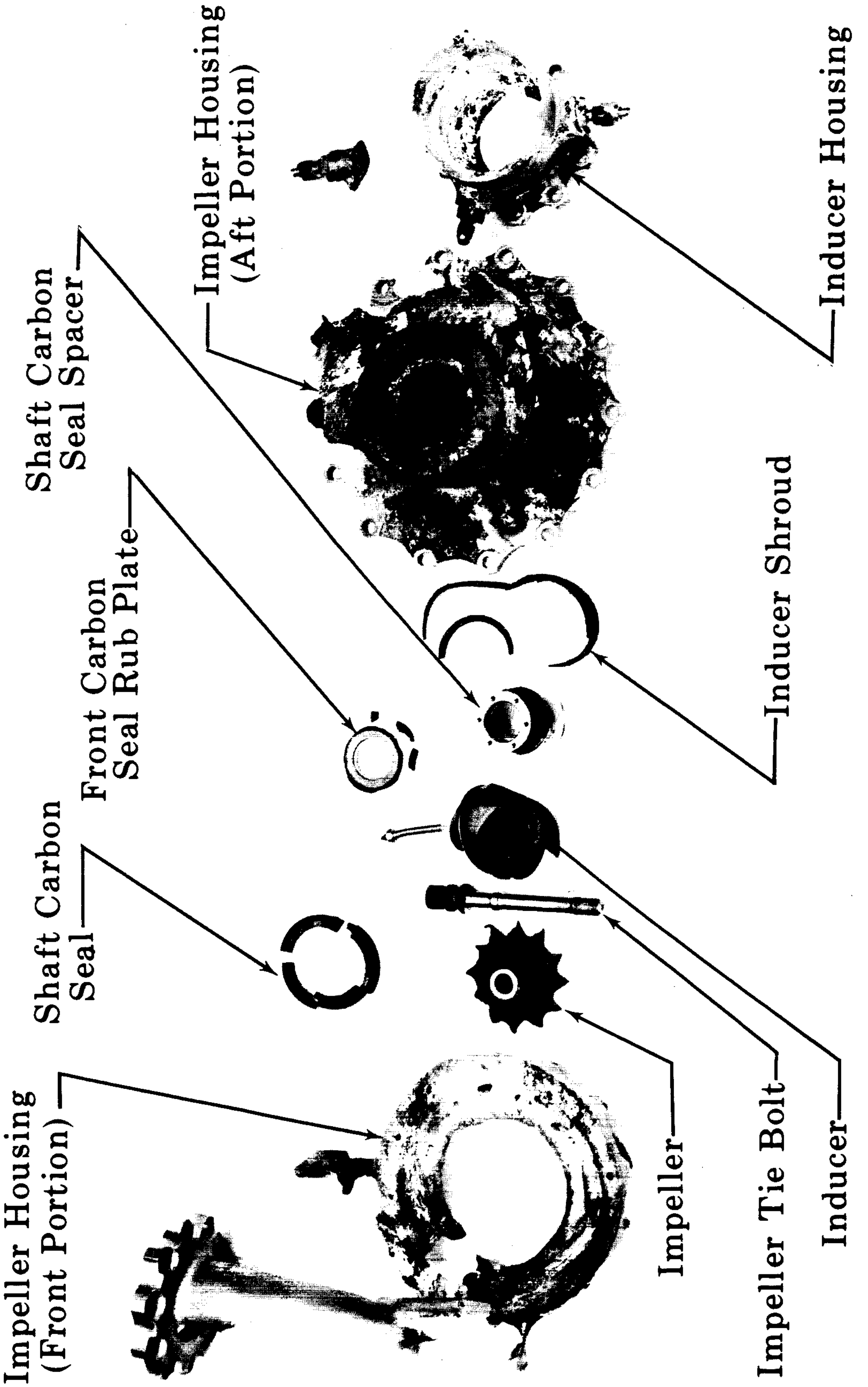


Figure II-13. RL10A-3-3 Oxidizer Pump Failure (Rig B71C003-11)



FD 18349

Figure II-14. RL10A-3-3 Oxidizer Pump Parts After Failure (Rig B71C003-11)

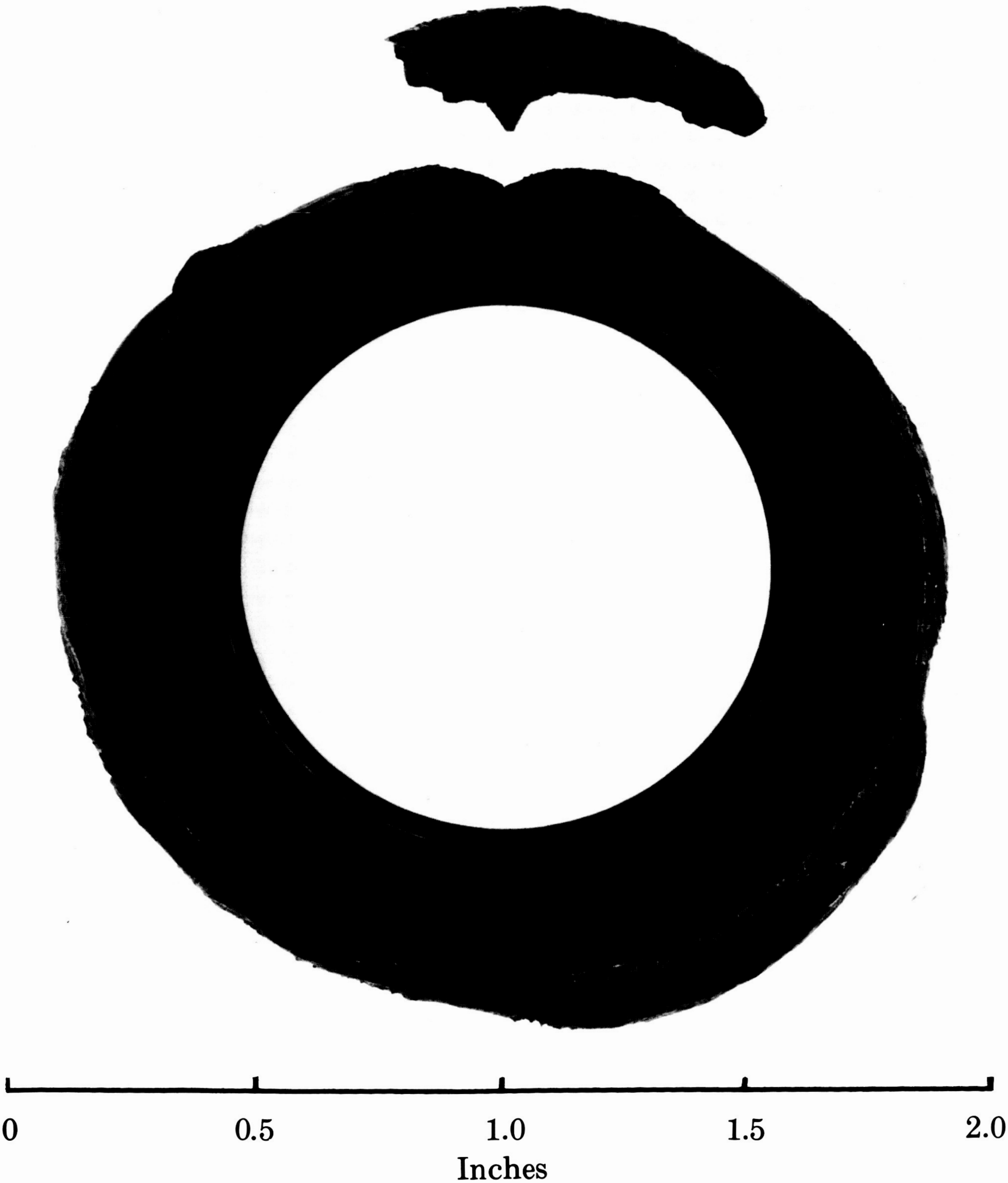


Figure II-15. RL10A-3-3 Oxidizer Pump Failed Front Bellows Seal Rub Plate (Rig B71C003-11) FD 18122

FD 18354

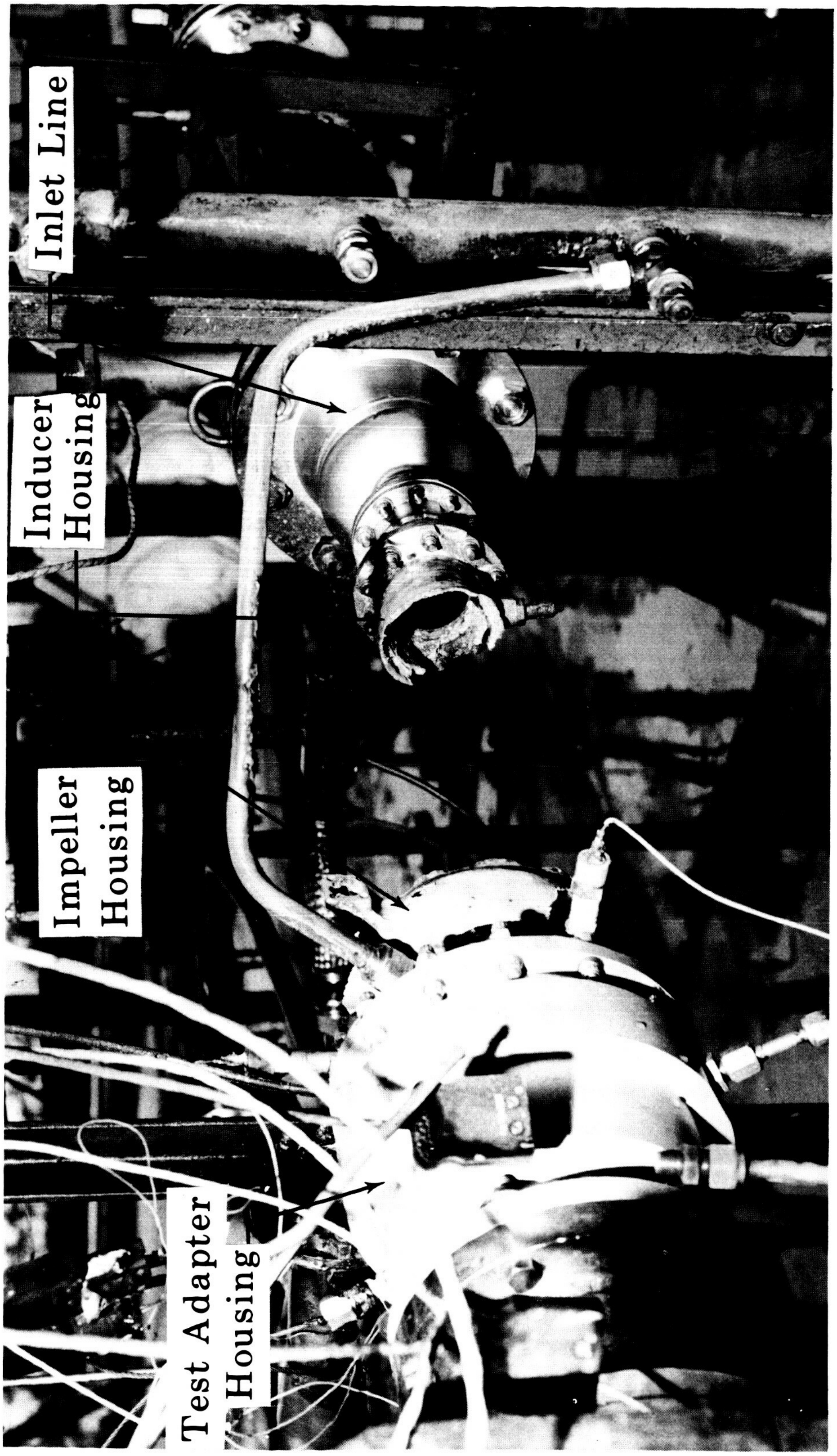
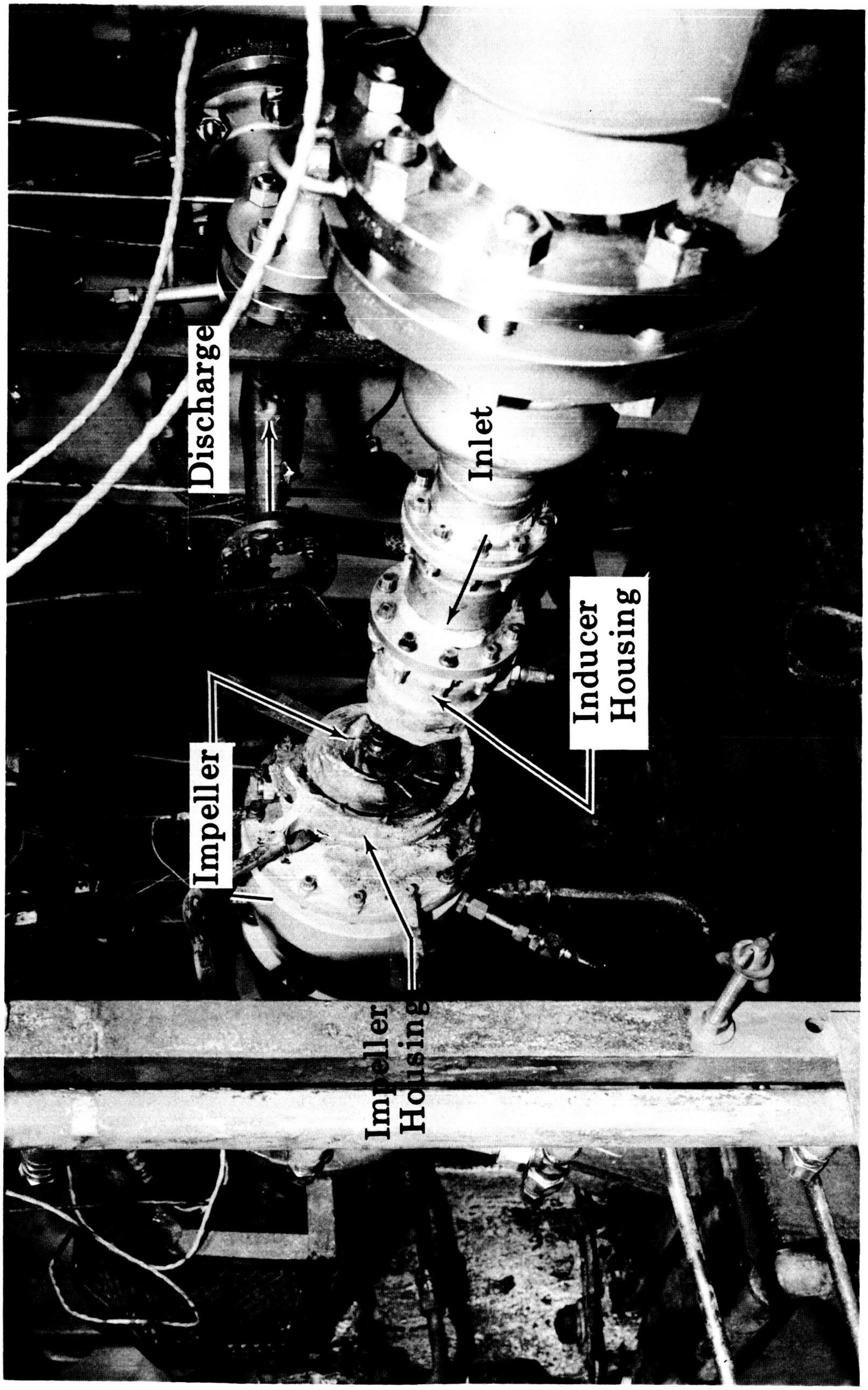


Figure II-16. RL10A-3-3 Oxidizer Pump Failure (Rig B71C003-12)



FD 18298

Figure II-17. RL10A-3-3 Oxidizer Pump Failure (Rig B71C003-12)

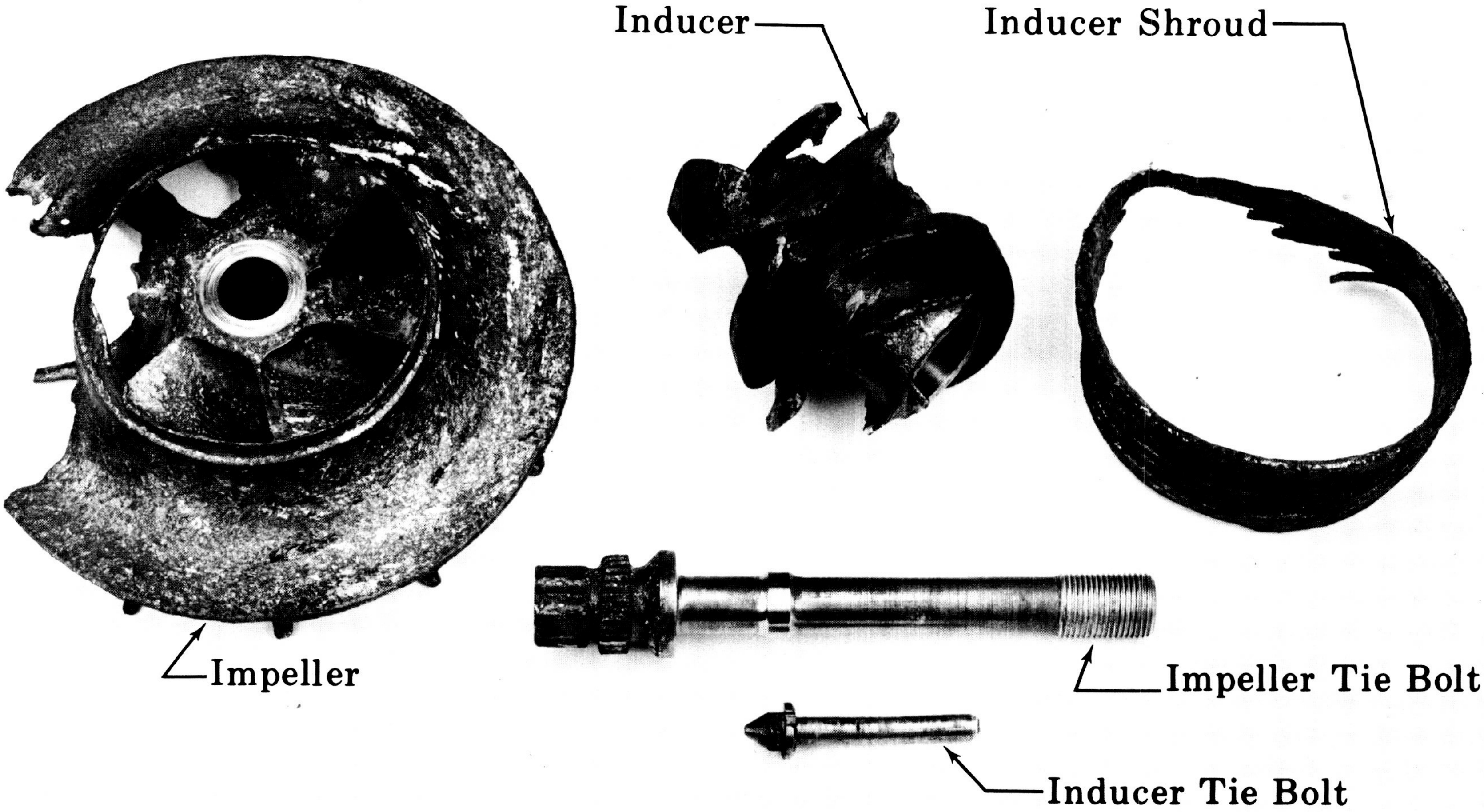
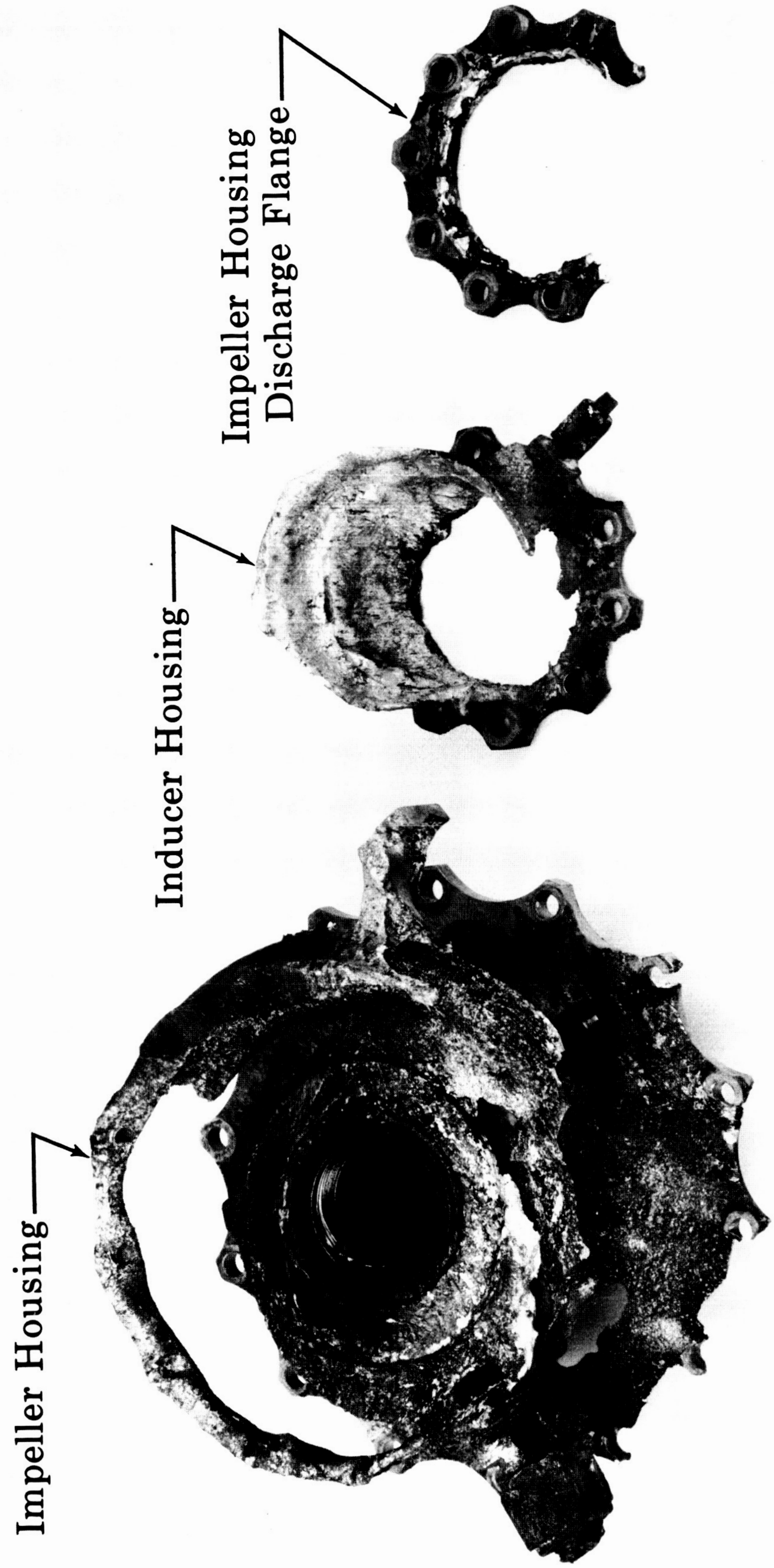


Figure **II-18.** RL10A-3-3 Oxidizer Pump Parts After Failure (Rig B71C003-12)

FD 18350



FD 18347

Figure II-19. RL10A-3-3 Oxidizer Pump Parts After Failure (Rig B71C003-12)

This program was conducted on rig B71C003, tests 13 through 16, table II-1 , and the results were:

1. The peak-to-peak pump discharge pressure fluctuation was 100 to 160 psi at the 6th order of pump speed with the increased diameter impeller as compared to 10 to 50 psi at the 2nd order of pump speed with the parts list impeller. During cavitation, the magnitude of the pressure fluctuations decreased for both configurations. The pump tested with the increased diameter impeller was run for a duration exceeding the time accumulated on either failed pump and no evidence of erosion or cracking in the cutwater areas was found. Thus, the high frequency, high pressure pulsations originating from the impeller blading were not detrimental to the cutwater in these tests. However, results may differ for operation with liquid oxygen because of the attendant higher density.

2. Inducer labyrinth seal and forward blade rubs resulted from the above tests, which included deep cavitation runs to 40%. There were no impeller rubs. Contact between the inducer and inducer housing was similar to that observed during previous engine and rig pump testing as seen in figures II-20, through II-22.

The rig was next tested with a parts list impeller in deep cavitation, pumping liquid oxygen,to determine if a fire could be started from a heavy inducer blade-to-housing rub. A heavy rub was expected since no bearing support to prevent shaft deflection would be obtained from the labyrinth seals-to-housing rub. A high clearance (0.180 in.) was set between the labyrinth seals and the housing to prevent rubbing in this area; any rubbing would be the inducer blading on the housing. No fires occurred during repeated test runs with the blade clearance initially set at 0.010 in. and the pump operating at the 40% cavitation levels. During these tests, the inducer blading wore approximately 0.033 in., which was greater than any previous experience.

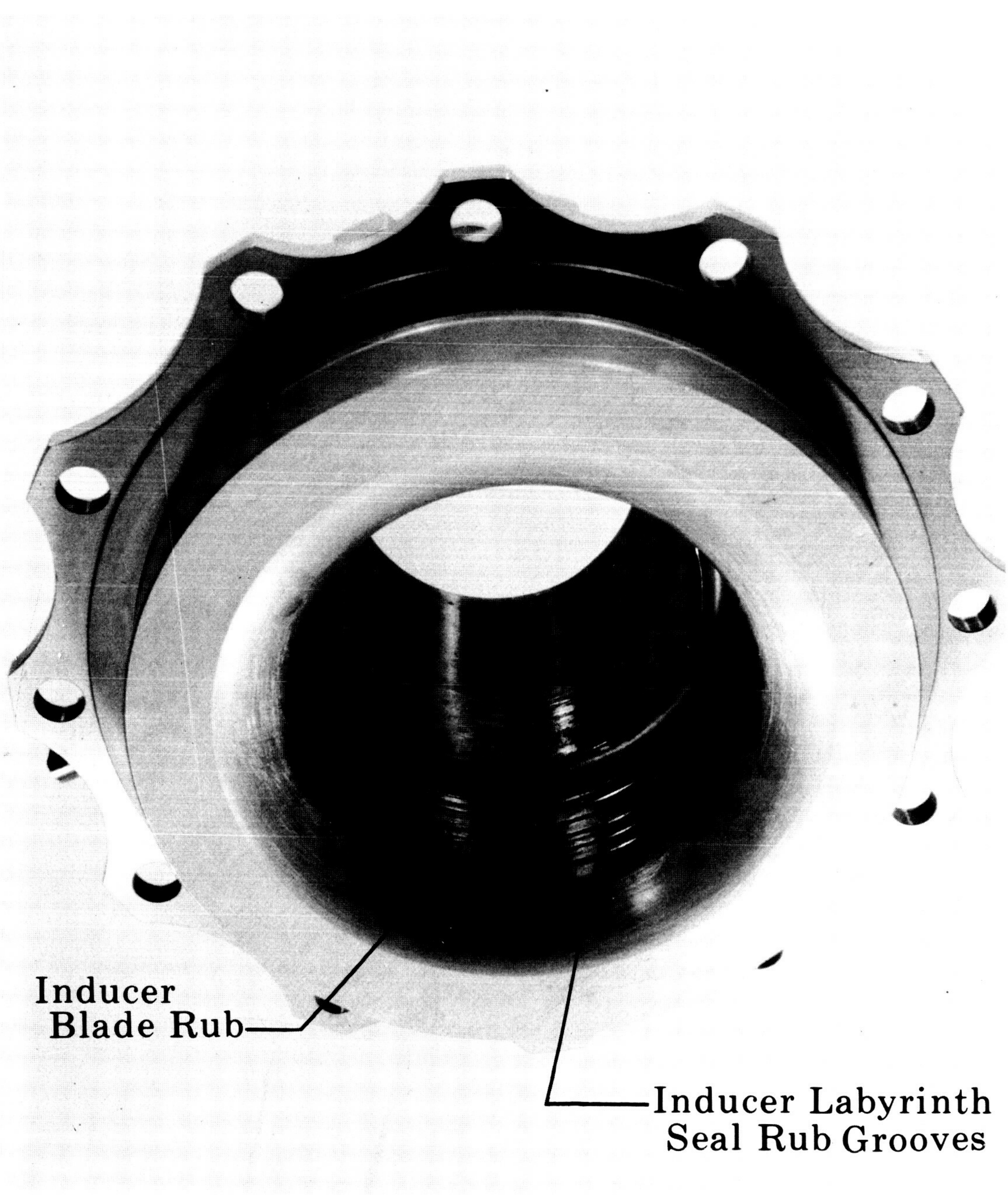


Figure II-20. RL10A-3-3 Oxidizer Pump Inducer Housing (Rig B71C003-15) FD 18328

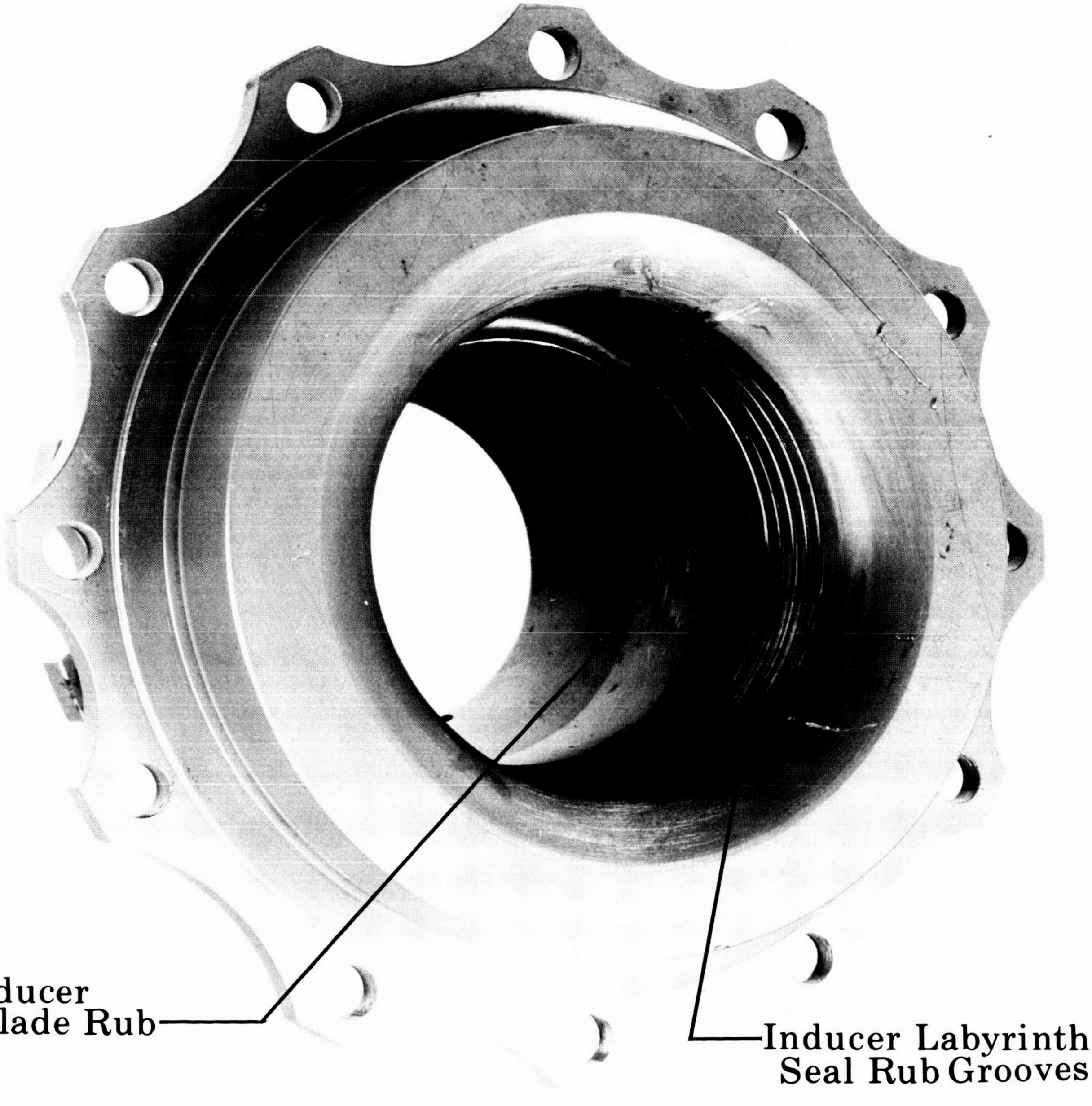


Figure II-21. RL10A-3-3 Oxidizer Pump Inducer Housing (Rig B71C003-16) FD 18327

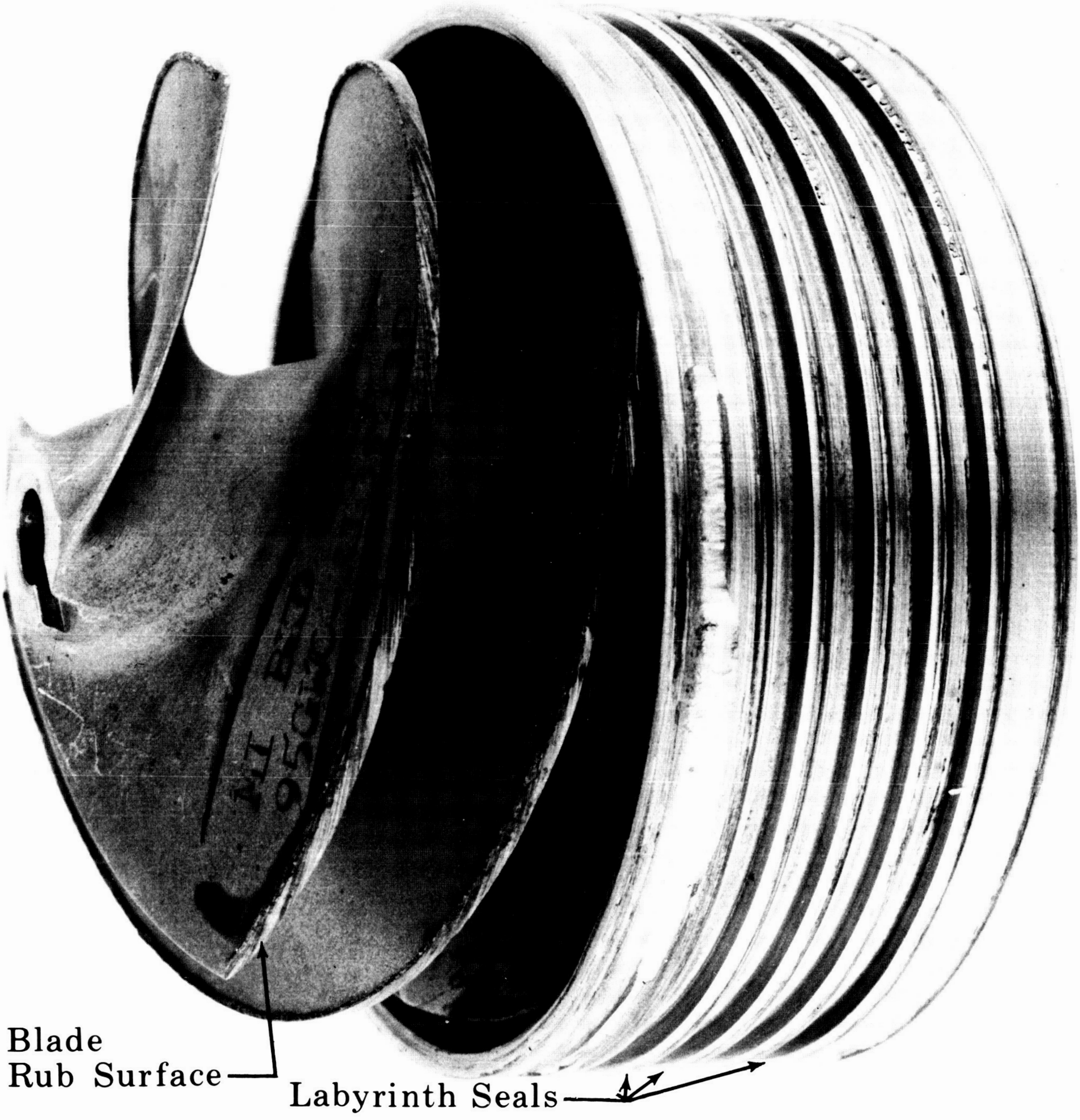


Figure II-22. RL10A-3-3 Oxidizer Pump Inducer Housing (Rig B71C003-16)

FD 18357

Pump tests were also conducted on special rub rig, B71C005, shown on figure II-5 with heavy inducer labyrinth seal-to-housing rubs. A wide blade clearance of 0.140 in. was set to prevent rubbing in the blade area. In these runs the inducer was forced against the inducer housing with a 1000-lb load applied radially at the thrust bearing support. Again no fire was produced. Labyrinth seal grooves to the depth of 0.014 in. were worn into the housing as can be seen in figure II-23.

The extensive past experience with labyrinth seal and inducer blading rubs, in addition to the results from the above tests, indicated that frictional heat resulting from an inducer seal or blade rub would not induce a fire. Sufficient cooling is available from the liquid oxygen preventing, in the rubbed area, a temperature rise high enough to sustain combustion.

The objective of the next test series was to determine if an impeller rub was the origin of the pump failures. To induce rubbing the impeller-to-housing axial clearances, forward and aft, were reduced as described below. The test fluid was liquid oxygen. The inducer clearance was increased to preclude inducer rubbing. Tests were conducted with the rear side impeller axial clearance reduced from 0.069 to 0.033 in. and then further reduced to 0.014 in. No rubbing occurred after pump operation to the 40% cavitation level. The impeller forward axial clearance was then set to a minimum of 0.027 in. After 40 minutes of pump operation, during the second cavitation run, a fire did occur. The clearance conditions were such that the impeller inner front contour could rub the inducer housing if there was radial deflection of the shaft. The resulting fire was similar to the two previous fires, and the pump parts are shown in figures II-24 through II-26. It was significant that the oxidizer pump thrust bearing ran in the forward rather than the normally rear direction, thus further reducing the forward impeller clearance by approximately 0.017 in. The bearing had also run in the forward position on the two previous pump fires, indicating that either an oversized impeller or reduced impeller shroud-to-housing front side clearance would reverse the pump thrust load. The fires could have been caused by impeller-to-housing rubs because of reversed thrust load combined with shaft and housing deflections.

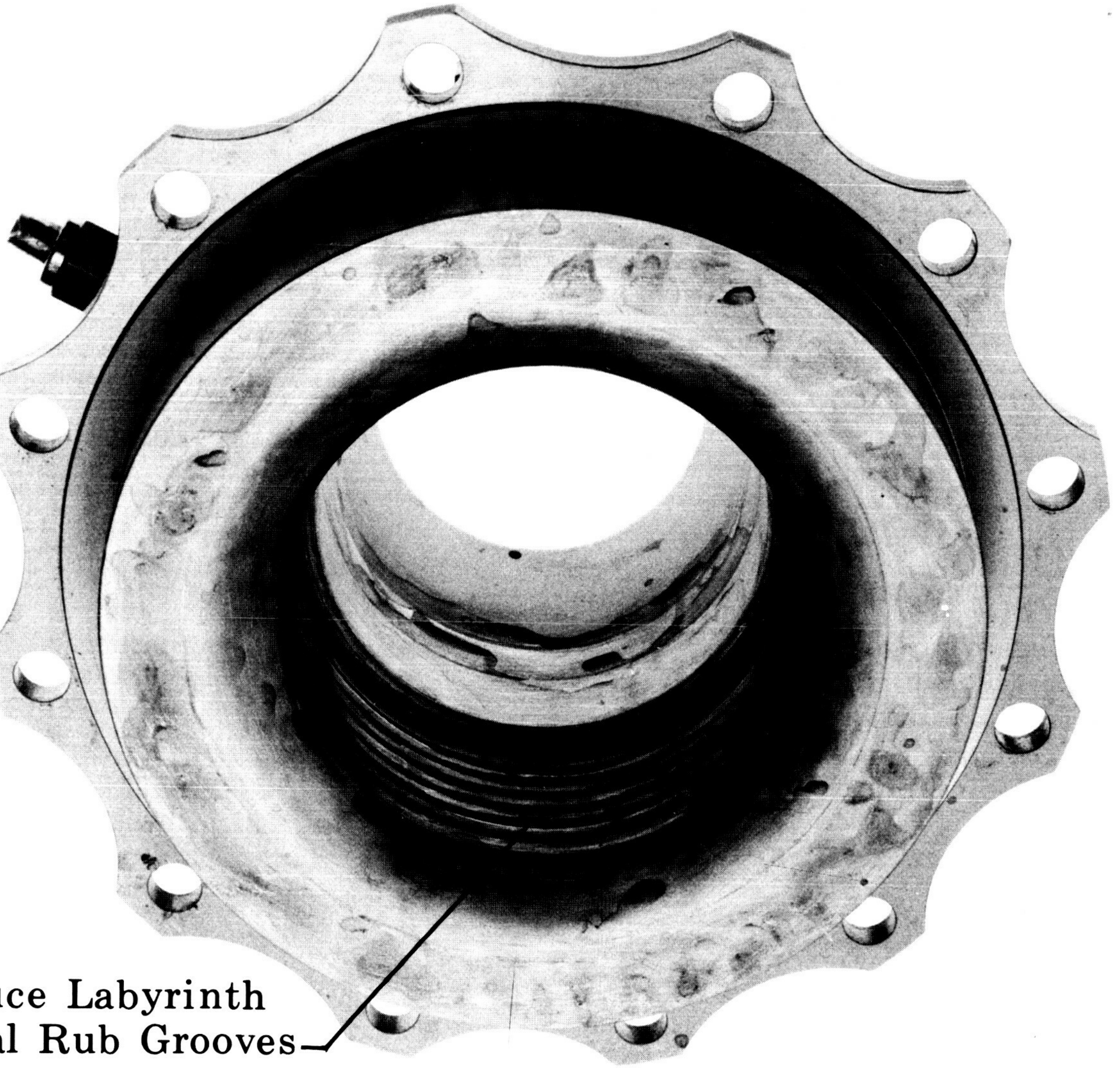


Figure II-23. RL10A-3-3 Oxidizer Pump Inducer Housing (Rig B71C005-3A) FD 18341

FD 18364

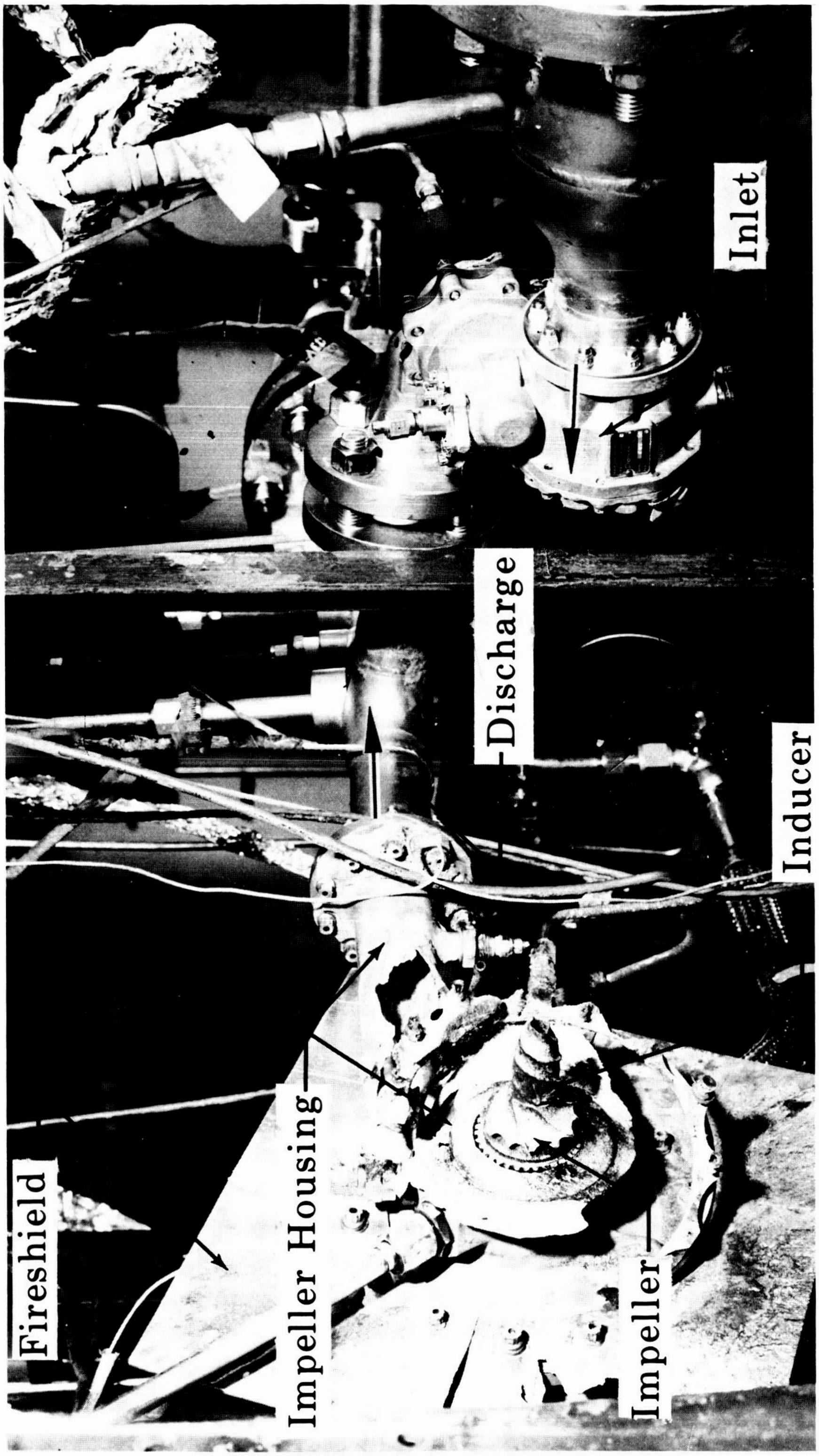


Figure II-24. RL10A-3-3 Oxidizer Pump Failure (Rig B71C003-21)

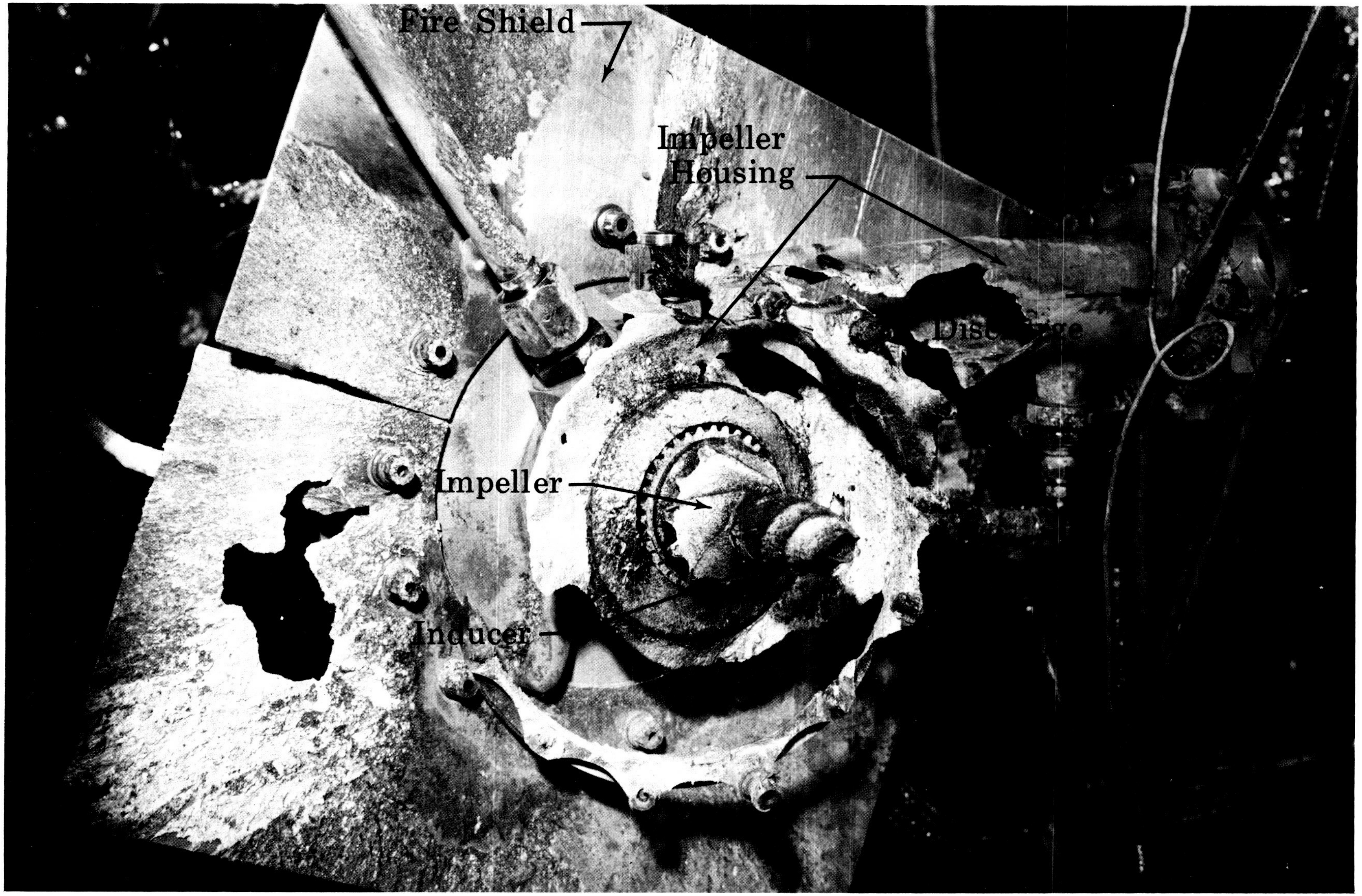
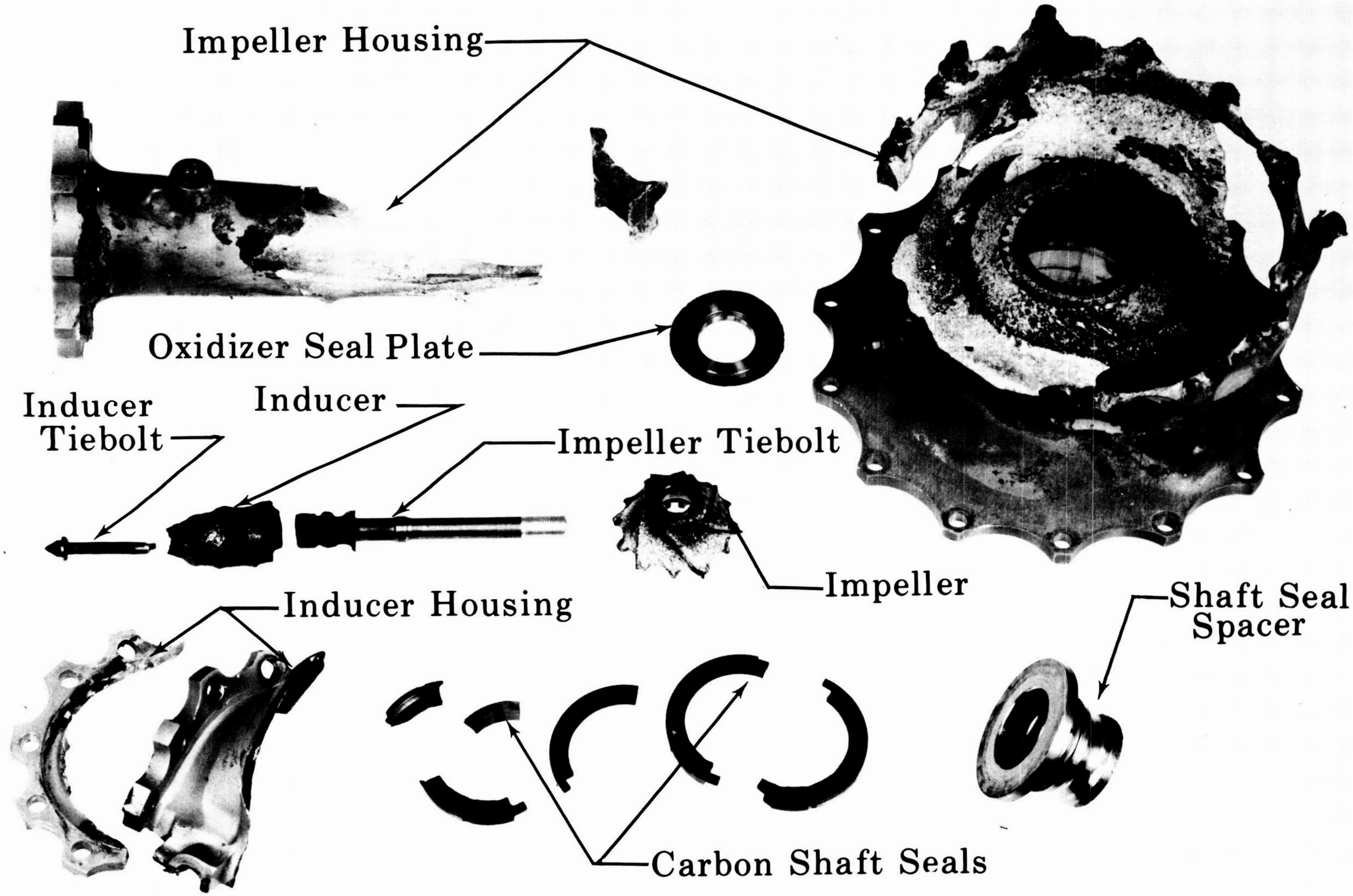


Figure II-25. RL10A-3-3 Oxidizer Pump Failure (Rig B71C003-21)

FD 18362



FD 18351

Figure II-26. RL10A-3-3 Oxidizer Pump Parts After Failure (Rig B71C003-21)

Duplicate tests, rig B71C003, tests 22 through 24, were conducted with liquid nitrogen to repeat the above conditions with standard impeller clearances in an attempt to induce impeller-to-housing rub without an attendant fire. These tests did not produce an impeller rub. However during the initial testing of oxidizer pump shaft deflection rig, B71C005, figure II-5 and test 1, table II-1, in liquid nitrogen an impeller rub was experienced. The pump configuration included a parts list impeller and opened inducer clearances. The impeller-to-housing forward axial clearance was 0.056 in. and the inducer blade and labyrinth diametrical clearances were 0.230 in. and 0.200 in., respectively, to ensure no contact with the inducer housing. The pump was recovering from a run in deep cavitation, and the pump shaft (movable in this rig) was in its center or parts list position, when the impeller rub was audibly detected. The forward face of the impeller shroud had rubbed the inducer housing as shown in figure II-27. No fire resulted since the pumped fluid was liquid nitrogen. It should be noted that similar operating conditions existed prior to the previous oxidizer pump fires, and this rub resulted from the same situation as previously described. This test demonstrated that an impeller-to-housing rub was possible and could have caused the previous pump fires.

A design study of the tolerances affecting the impeller-to-housing axial clearance was initiated to determine the cause of this rub and to determine if this rub could have occurred on the previous fires. Results of this study are described for the first fire and are representative of study results for each fire. For the first pump fire the impeller-to-housing forward clearance was measured to be 0.051 in. at the impeller OD. The design study showed that the minimum clearance did not occur at the impeller tip, but was located along the impeller contour near the bore. This minimum clearance was 0.032 in. with the oxidizer pump rotor running in the normal rearward position on the thrust bearing. The shaft was actually running in the forward position on the thrust bearing as determined from inspection of the bearing and this reduced the clearance to 0.022 in. Radial and axial thermal growths of the pump shaft and housing lowered this clearance an additional 0.004 in. The average shaft-to-housing stackup concentricities of 0.005 in. added to the contour tolerances of 0.006 in. could have reduced the running clearances, without any shaft deflection, to a minimum of 0.007 in. Therefore, at extreme thermal and tolerance conditions, a shaft deflection of 0.007 in. could cause an impeller rub. Deflections exceeding these values, as determined from measurement of the depth of inducer rubs, were observed during previous testing. The relationship between inducer radial deflection and impeller-to-housing deflection is shown in figure II-28. With 0.012-in. inducer blade tip movement, a 0.010-in. impeller deflection toward the inducer housing also occurs. Thus both the design study and test experience verified that an impeller rub was the probable cause of the fires.

In addition to the design analysis a series of static deflection tests was conducted on the oxidizer pump shaft and housings. The objectives were to determine:

1. The deflections of the shaft and housing over a representative load range
2. If structural changes would be required to reduce these deflections during pump operation.

Three series of tests were conducted, the first with only the rotating assembly mounted rigidly at the front bearing location, the second with the rotating assembly mounted in the engine housings that were in turn mounted to a rigid support, and the third with a complete turbopump mounted in an engine.

The test configuration for measuring shaft deflection only is shown in figure II-29. The rig during a typical test is shown in figure II-30. The radial load and bending moment relationship from the unsymmetrical pressure distribution around the impeller and inducer are presented in figure II-31. The maximum differential in pressure around the impeller was 15 psid as determined from testing. This results in a radial load of approximately 75 lb. Deflection test results for the oxidizer pump shaft compared with the predicted deflection values are shown in figure II-32. A significantly high load, approximately 300 to 500 lb, was required to produce an impeller movement of 0.010 in. This was much higher than the maximum load of 75 lb calculated from test data. The shaft deflection characteristics taken at 400-lb radial load, shown in figure II-33, represent a normal deflection curve for a cantilever beam, indicating no unusual deflection characteristics.

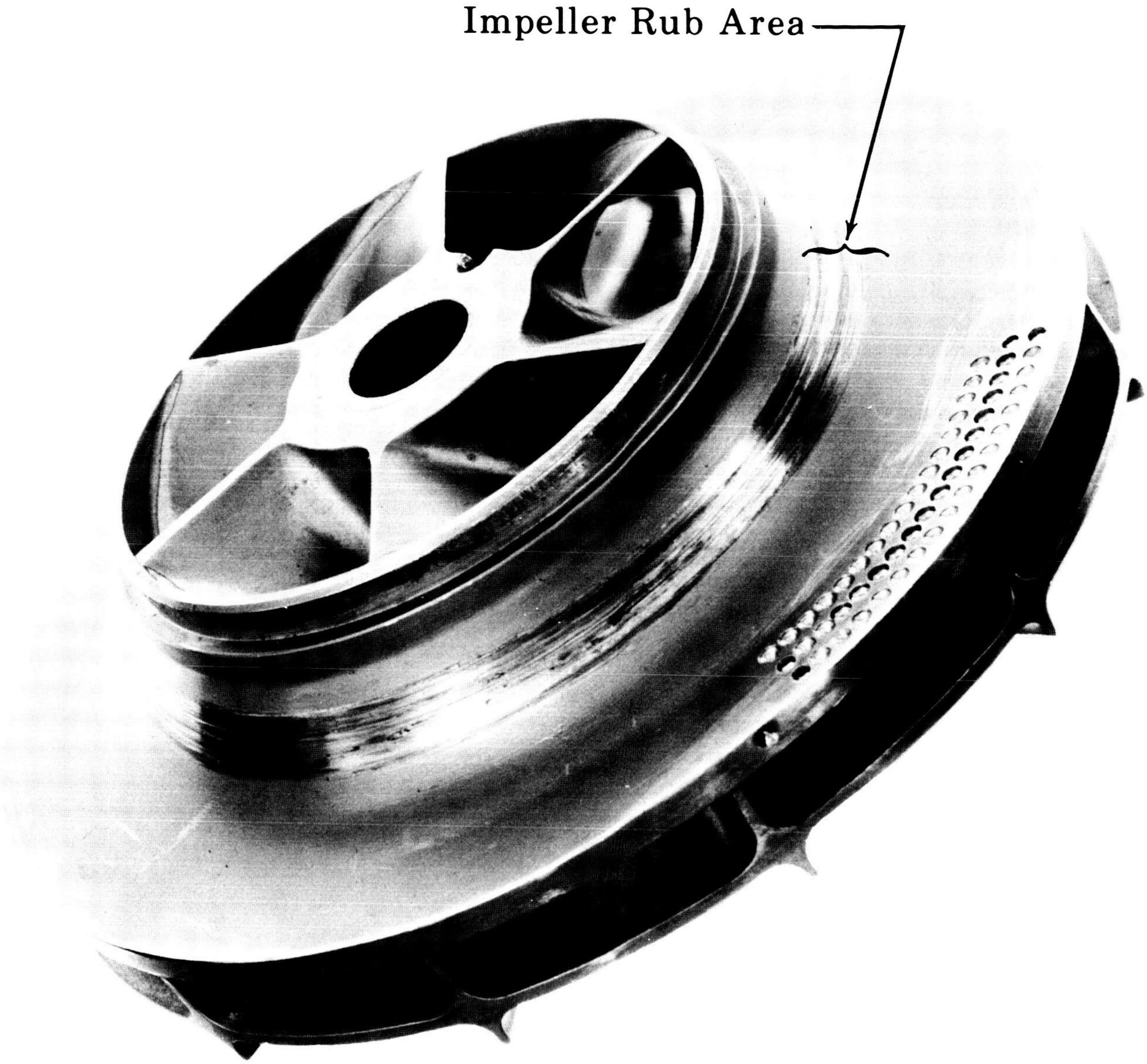


Figure II-27. RL10A-3-3 Oxidizer Pump Impeller (Rig B71C005-1) FD 18355

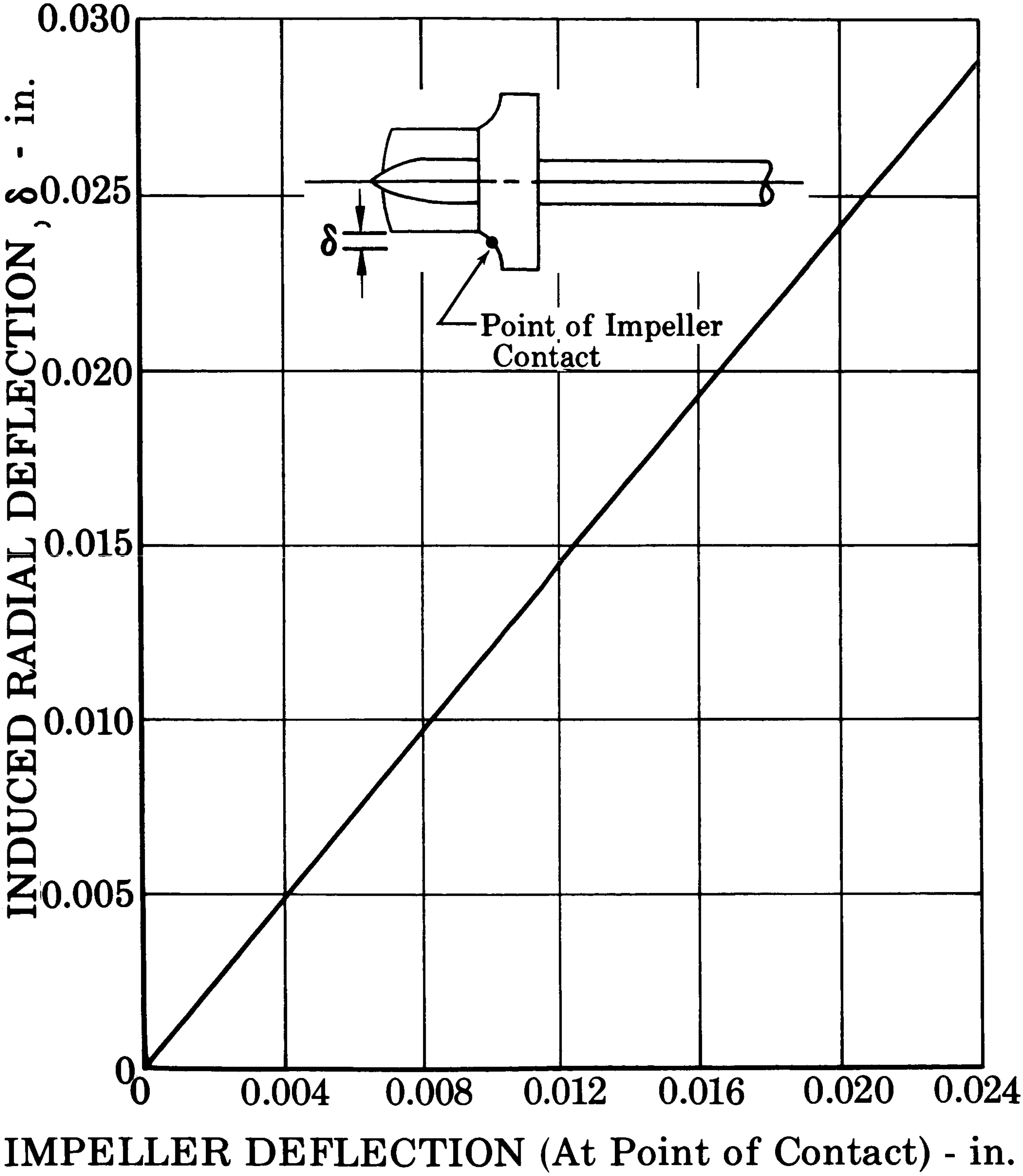
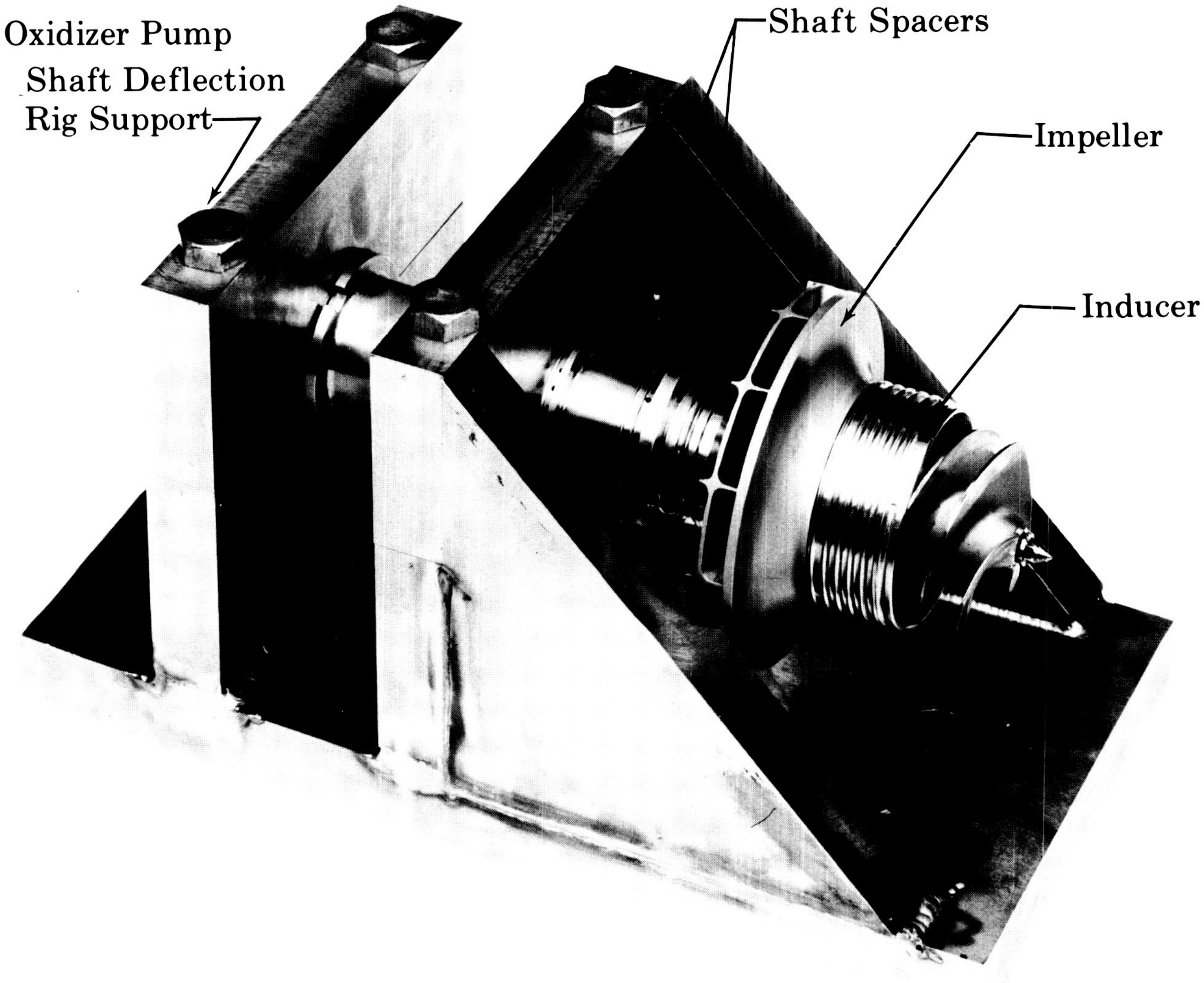


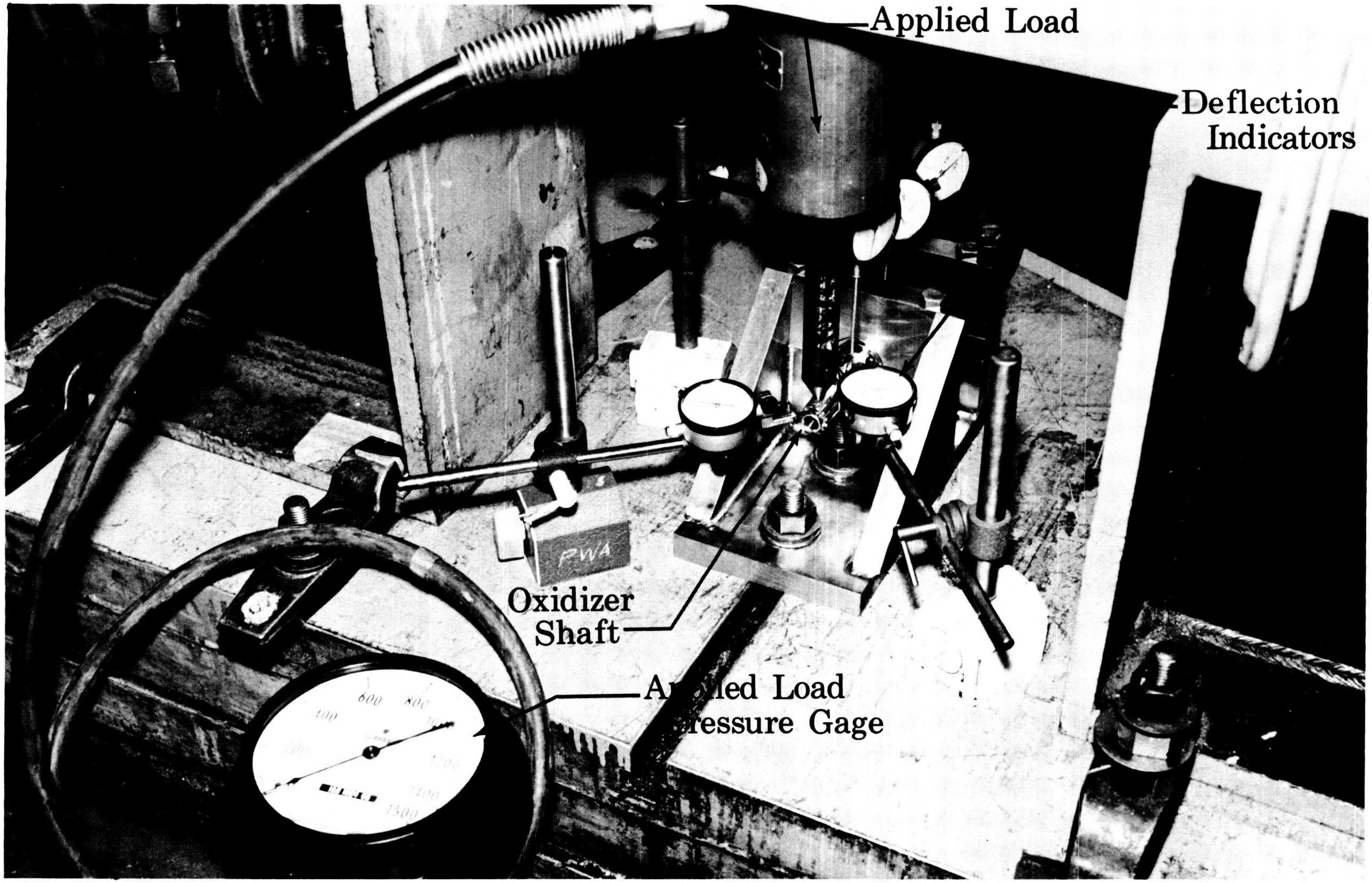
Figure II-28. RL10A-3-3 Oxidizer Pump Inducer Radial Deflection vs Impeller Deflection

FD 18326



FD 18346

Figure II-29. Oxidizer Pump Shaft Deflection Rig Support



FD 18348

Figure II-30. Oxidizer Pump Shaft Deflection Rig

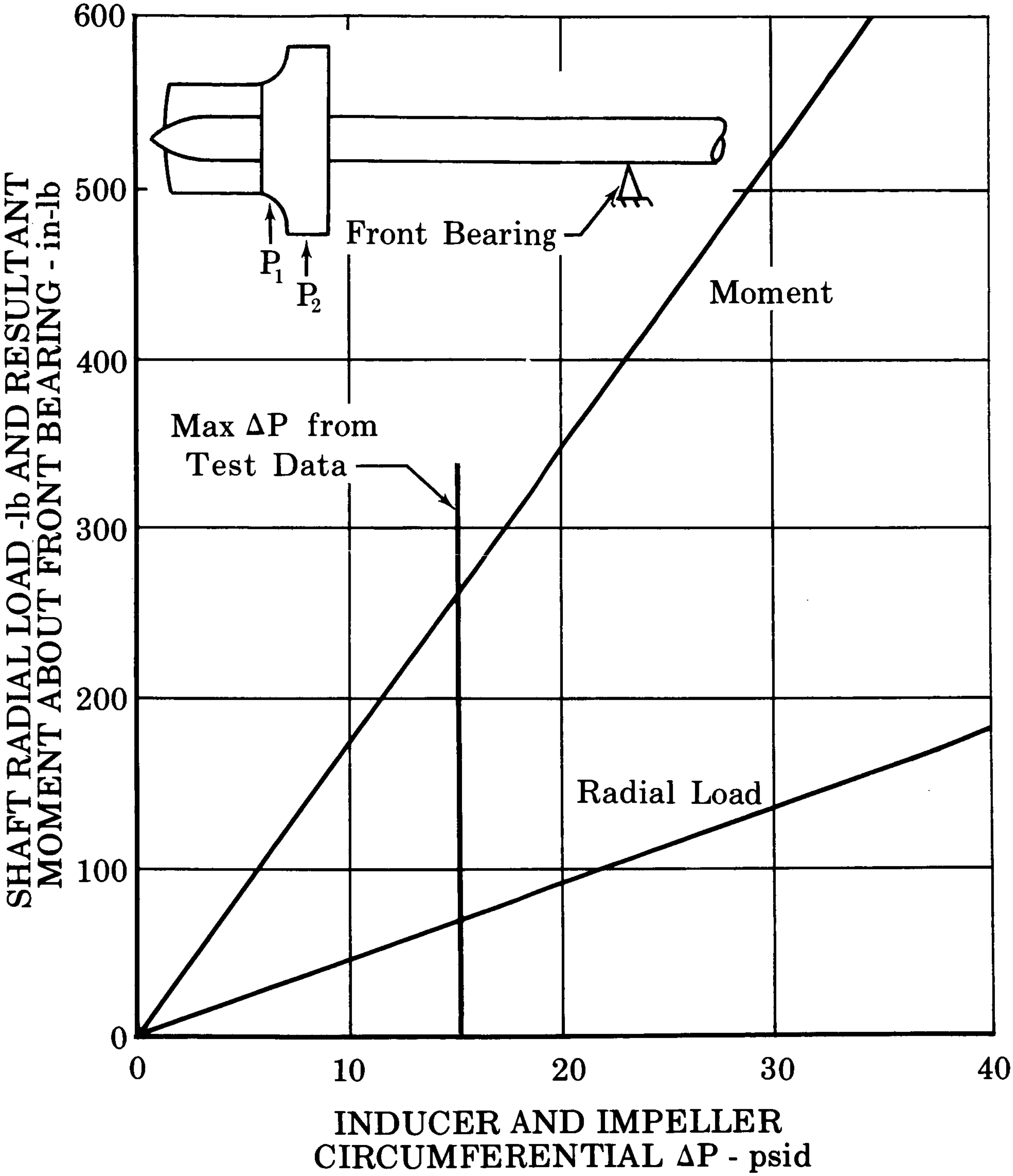


Figure II-31. RL10A-3-3 Oxidizer Pump Shaft Radial Load and Moment vs Inducer and Impeller Circumferential Pressure Difference FD 18359

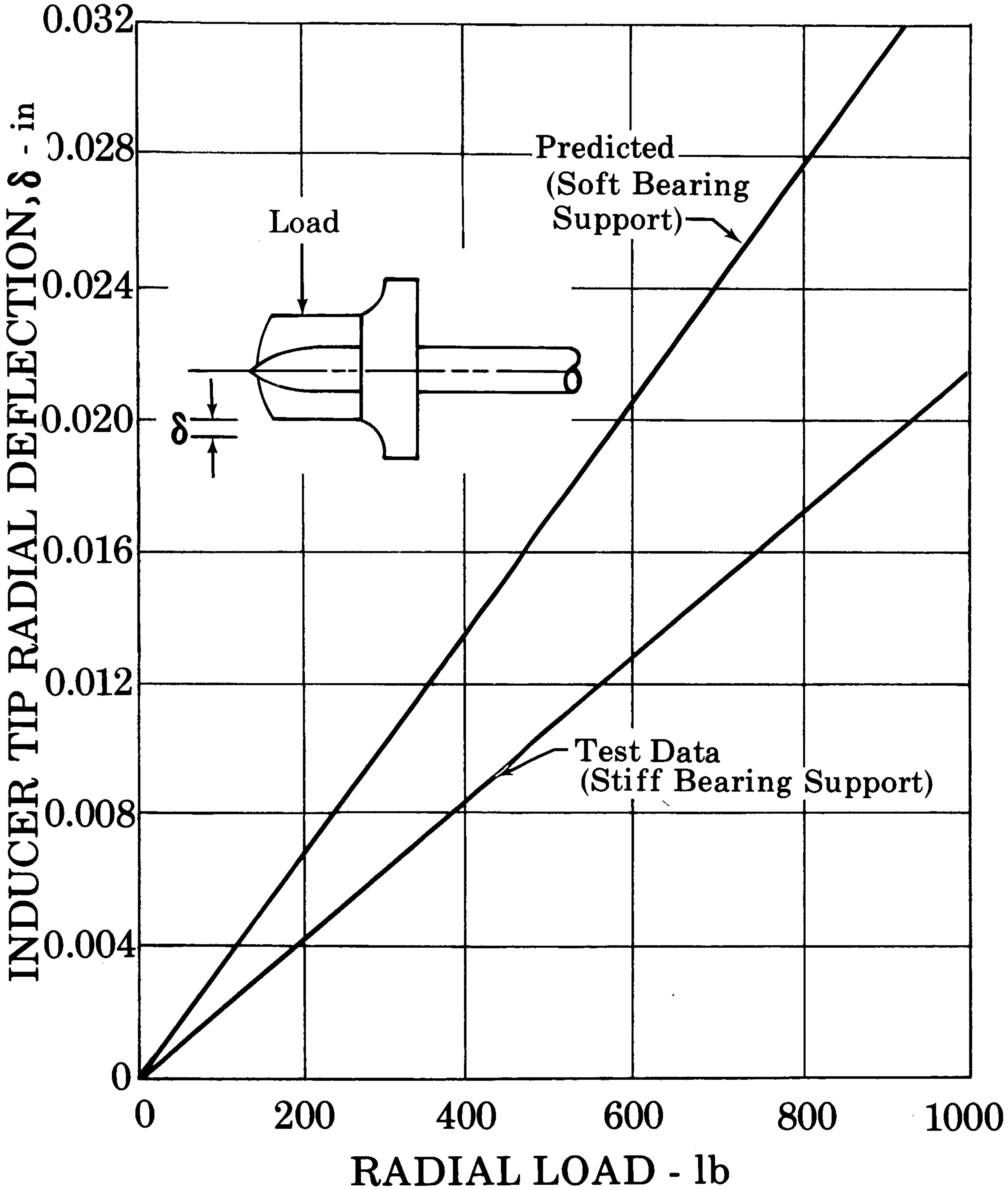
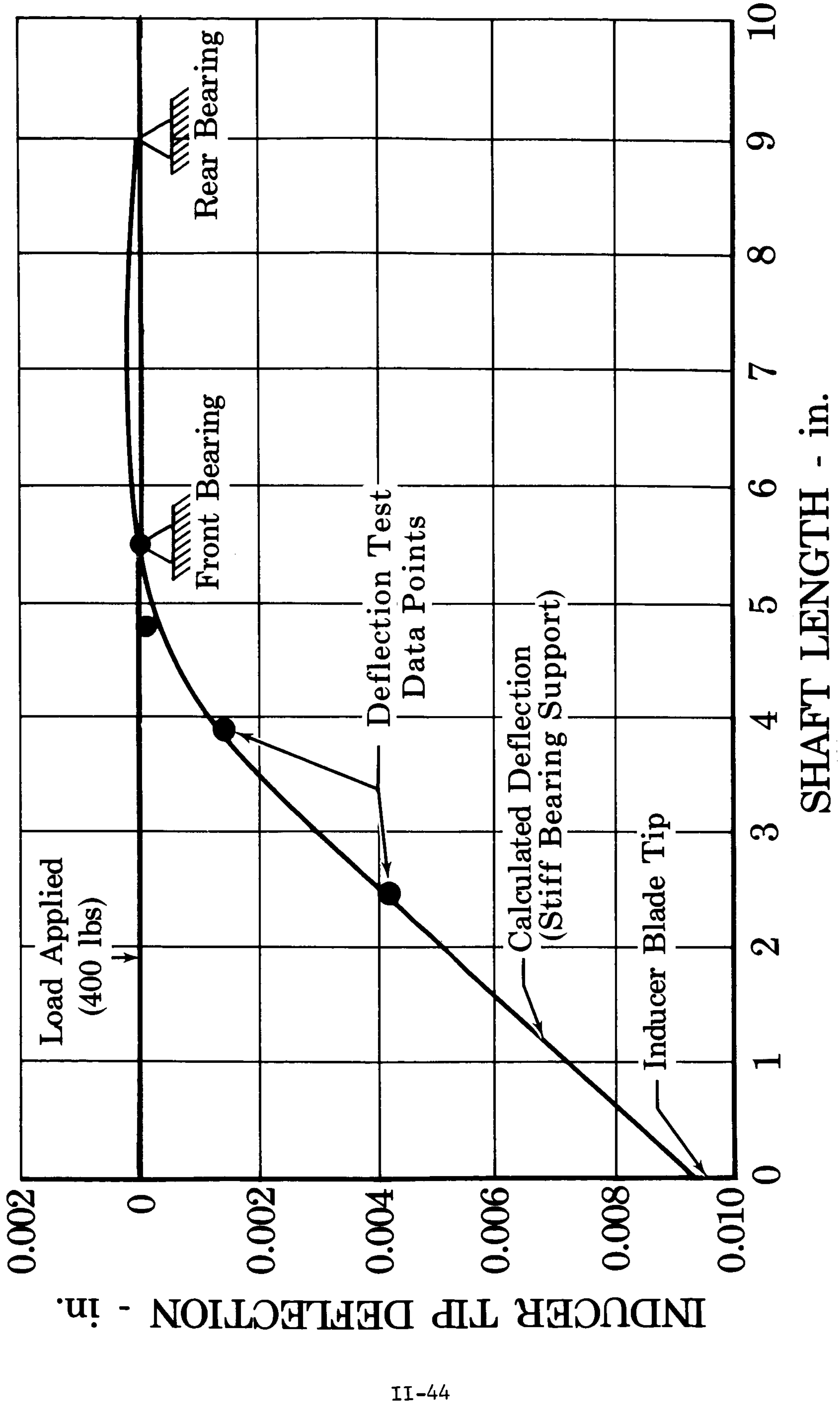


Figure II-32. RL10A-3-3 Oxidizer Pump Inducer Tip Radial Deflection vs Radial Load

FD 18361



FD 18343

Figure II-33. RL10A-3-3 Oxidizer Pump Inducer Tip Radial Deflection vs Shaft Length

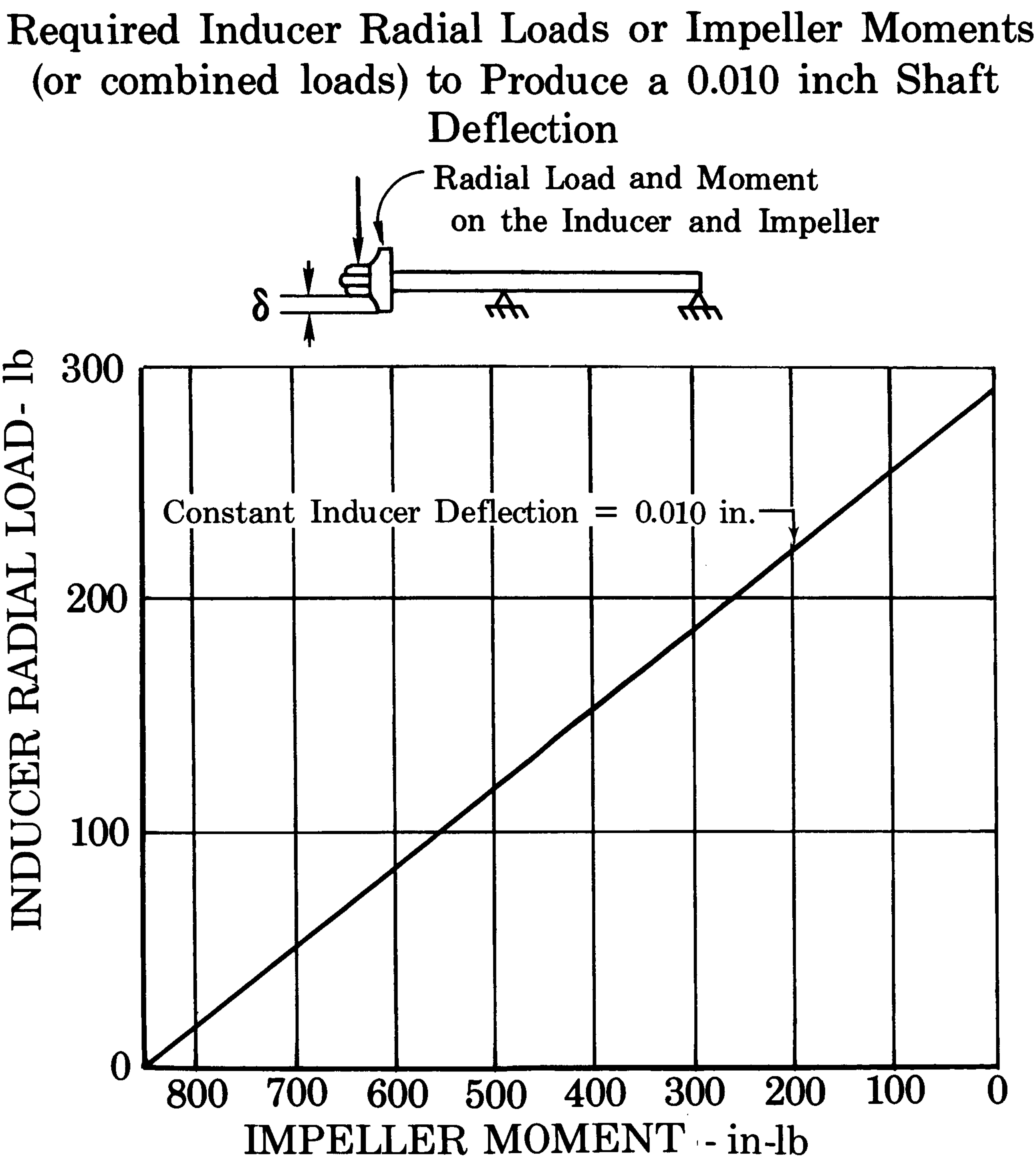


Figure II-34. Calculated RL10A-3-3 Oxidizer Pump Inducer Radial Load vs Impeller Moment FD 18325

These data suggest that additional radial forces must be acting on the inducer and impeller or on the housing to cause the rubs observed during pump testing. To produce a 0.010-in. shaft deflection from a pure moment, 850 in.-lb is required, figure II-34, as compared to a maximum moment of 260 in.-lb determined from pump tests, figure II-31. A plot showing the calculated individual radial load or moment of the impeller and inducer and/or a combination required to produce a 0.010-in. shaft deflection is presented in figure II-34. It should be noted that the necessary differential pressure around the impeller and inducer to produce these forces was not observed during pump testing.

With the inducer housing removed, deflection tests were continued on an assembled oxidizer pump. A load was applied at the center of the inducer with an equal and opposite load applied to the impeller housing forward flange as shown in figure II-35. The deflection curves, presented in figure II-36, compared closely to previous tests (measured values, figure II-32). The impeller housing deflection was minor.

A substantial deflection of the inducer forward flange was measured during tests with the turbopump mounted on an engine. The test configuration for loading the inducer flanges is shown in figure II-37. Both shear and moment loads were applied at representative radial directions to the maximum allowable installation values of 200 lb and 2200 in.-lb, respectively. Inducer housing front flange deflections from 0.008 to 0.013 in. were recorded. Therefore, engine or rig installation flange loads can cause a reduction in the inducer radial and impeller axial clearances.

The conclusions reached from the investigation described above were:

1. The oxidizer pump fires resulted from a rub between the impeller and the housing

2. The rub was caused by a combination of:

    a. Side and vibrational loads on the rotating assembly and housing that were higher than expected during operation in deep cavitation. These were aggravated by the experimental, increased diameter pump impeller.

b. Increased inducer labyrinth seal clearance. This allowed greater deflection of the inducer relative to the housing so that impeller rub could occur before the inducer rubbed and restrained the shaft.

c. Increased inducer labyrinth seal clearance that, because of increased recirculation leakage, caused a decreased pressure on the front side of the impeller, causing the rotor to run in the forward position.

d. Less than desirable impeller-to-housing minimum design clearances.

The above combination of parts and circumstances would not occur during engine operation. However, for additional margin the parts list impeller-to-housing clearances were increased. With this design, conditions as severe as encountered in the rig testing would not cause an impeller-to-housing rub.

D. OXIDIZER PUMP INDUCER HOUSING CARBON INSERT TESTING

To complete the original program objective, i.e., elimination of metal-to-metal rubbing of the inducer on the housing, testing of an inducer housing was initiated with an abradable carbon insert, similar to the oxidizer pump design in previous RL10 engine models. Carbon was selected because of the extensive satisfactory experience on previous RL10 engine models totaling more than 5500 firings and 800,000 seconds of engine test time. This design required an increased inducer blade-to-housing clearance to prevent any possible blade rub because of the expected increased wear of the carbon material when rubbed by the inducer labyrinth seal as compared to aluminum. The blade diametrical clearance, therefore, was increased in steps from 0.050 to 0.100 in. while the labyrinth seal was set to the parts list diametrical clearance of 0.010 in., reference tests 1 through 4 of rig B71C006, table II-1. The test results, figures II-38 through II-41, show that performance with blade clearances up to 0.100 in. met specification requirements. The labyrinth seals rubbed as expected, but there were no blade rubs as seen in figure II-42.

FD 18342

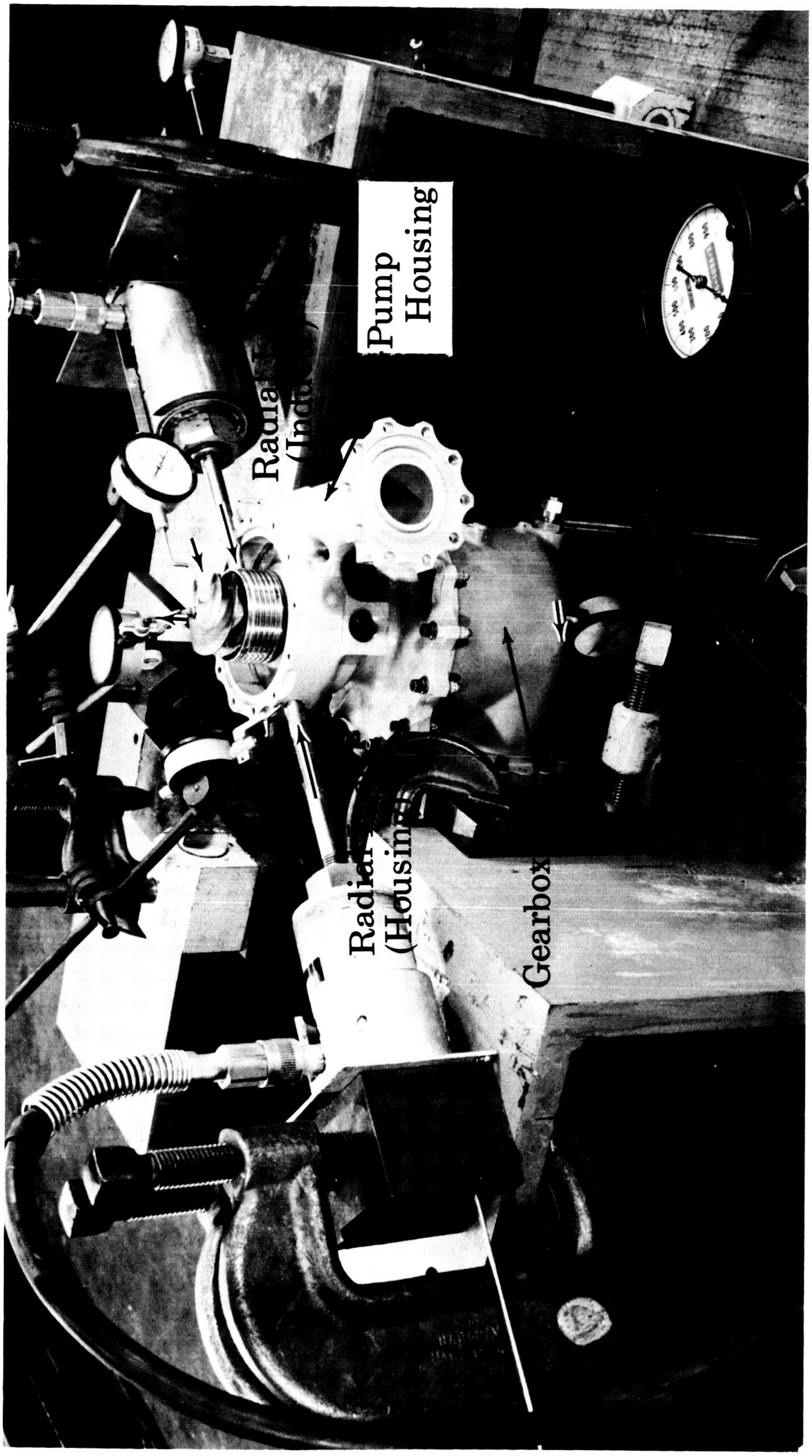


Figure II-35. Oxidizer Pump Deflection Test Rig

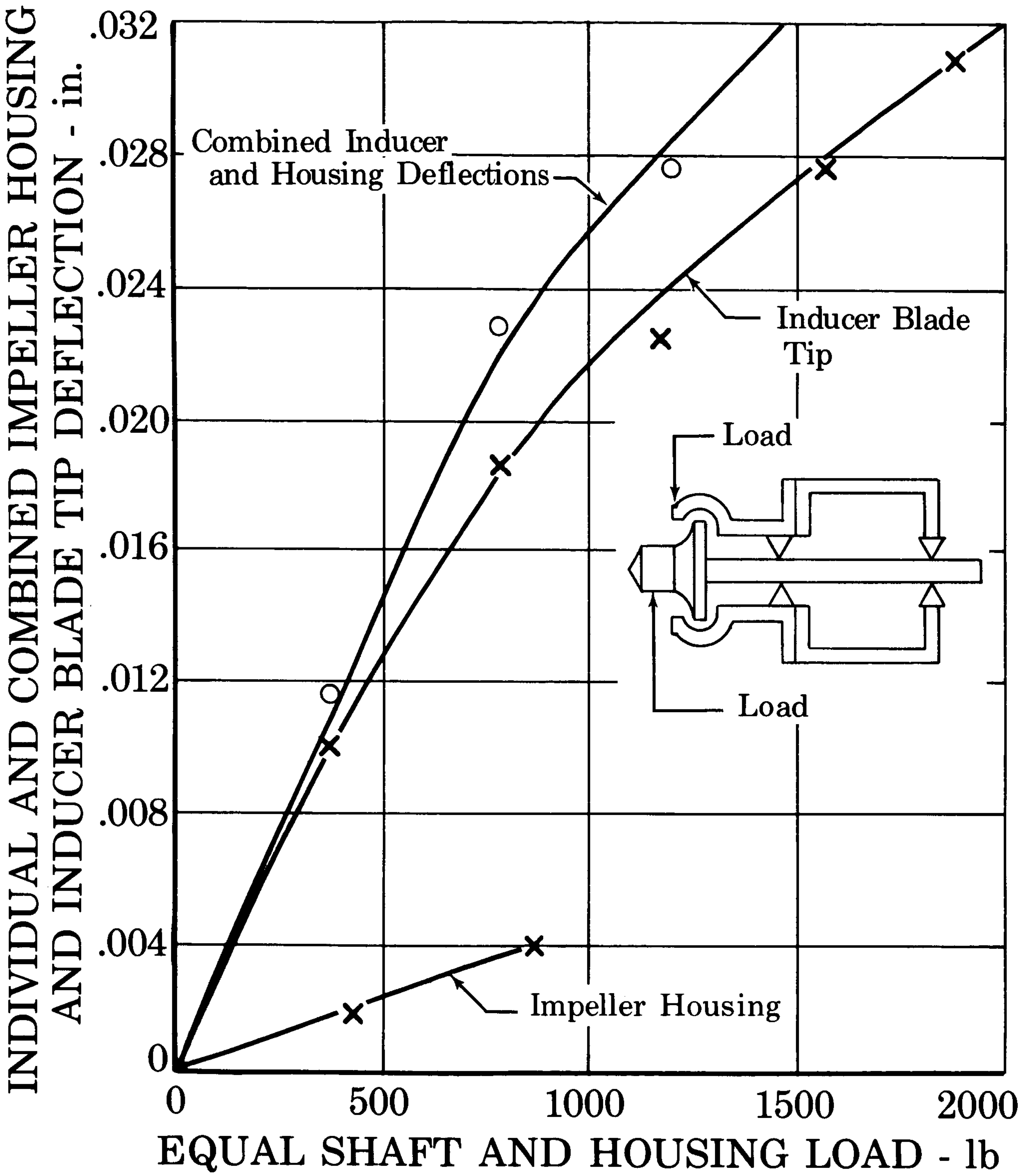


Figure II-36. RL10A-3-3 Oxidizer Pump Impeller Housing and Inducer Blade Tip Deflection vs Applied Load FD 18324

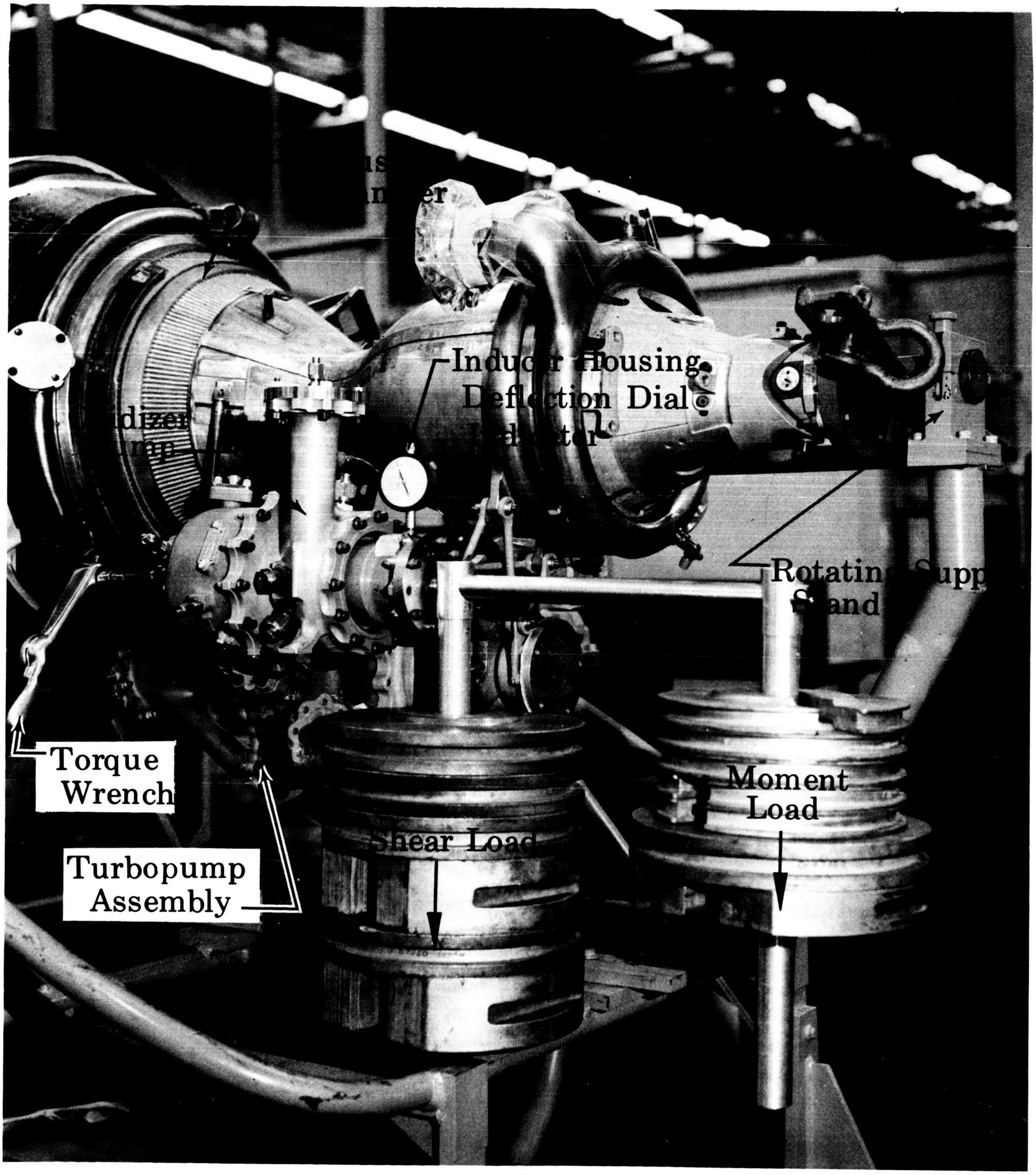


Figure II-37. Oxidizer Pump Inducer Flange Deflection Test Rig

FD 18368

DF 50261

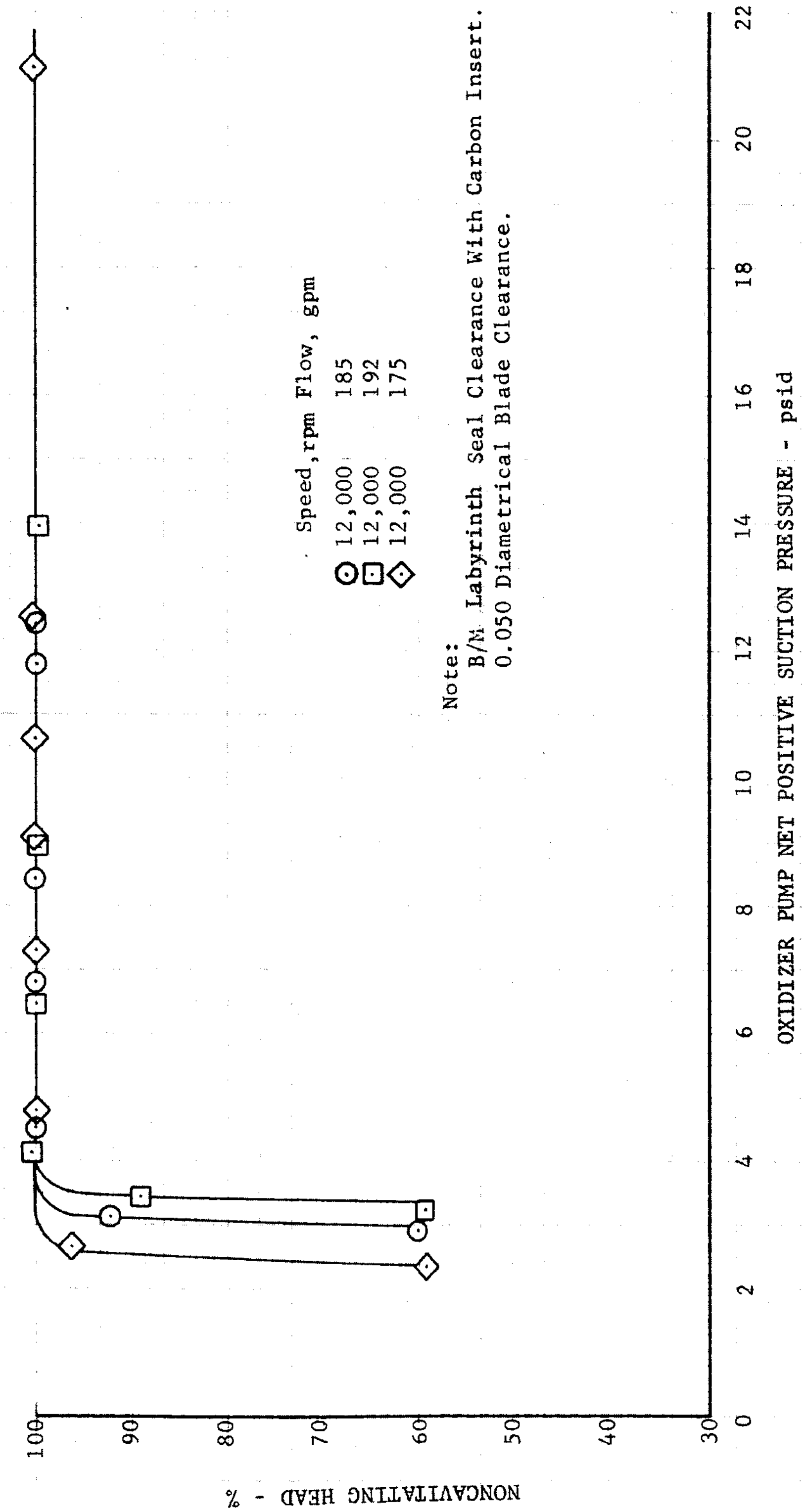


Figure **II-38.** RL10A-3-3 Oxidizer Pump NPSP Performance (Rig B71C006-1)

DF 20562

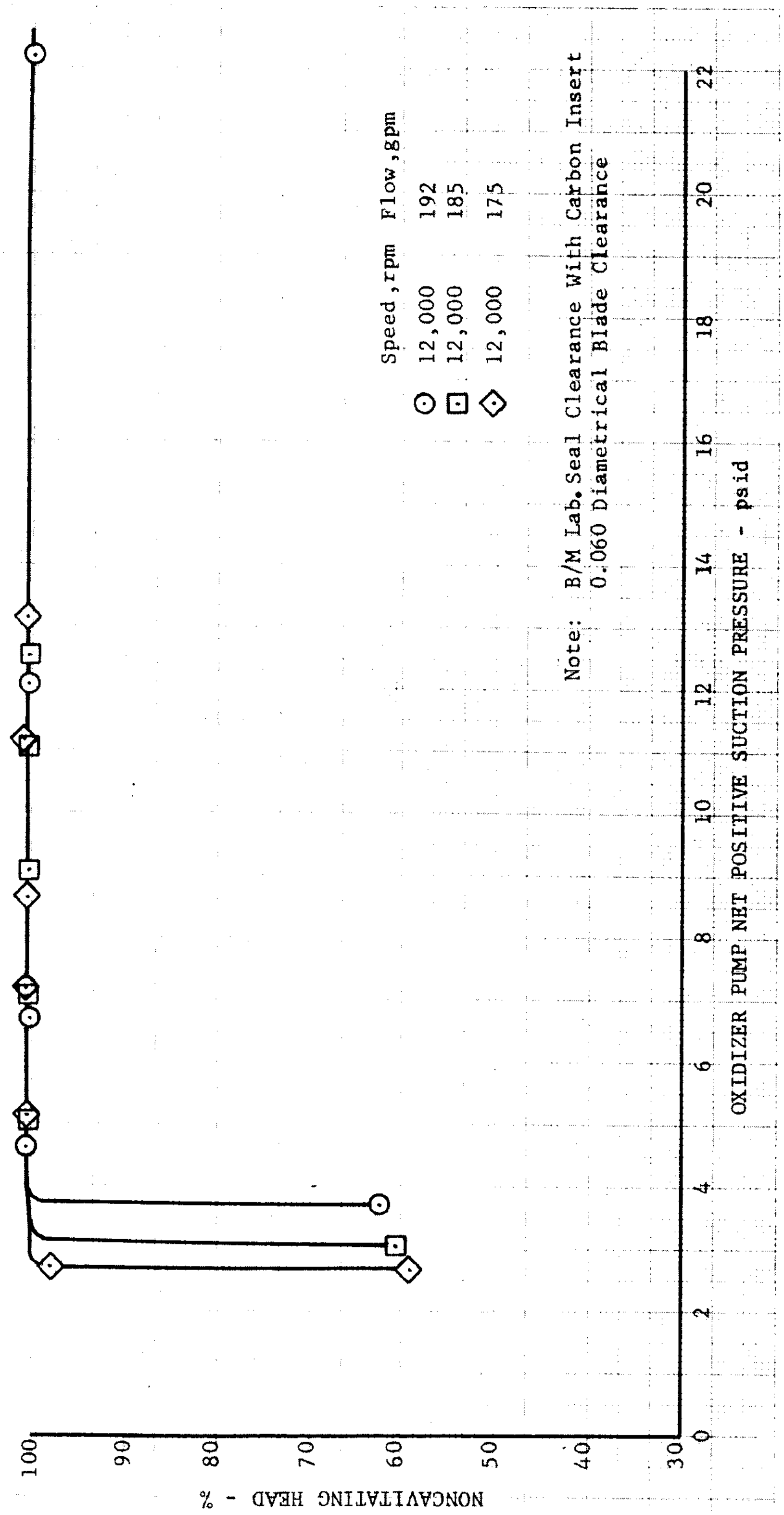


Figure II-39. RL10A-3-3 Oxidizer Pump NPSP Performance (Rig B71C006-2)

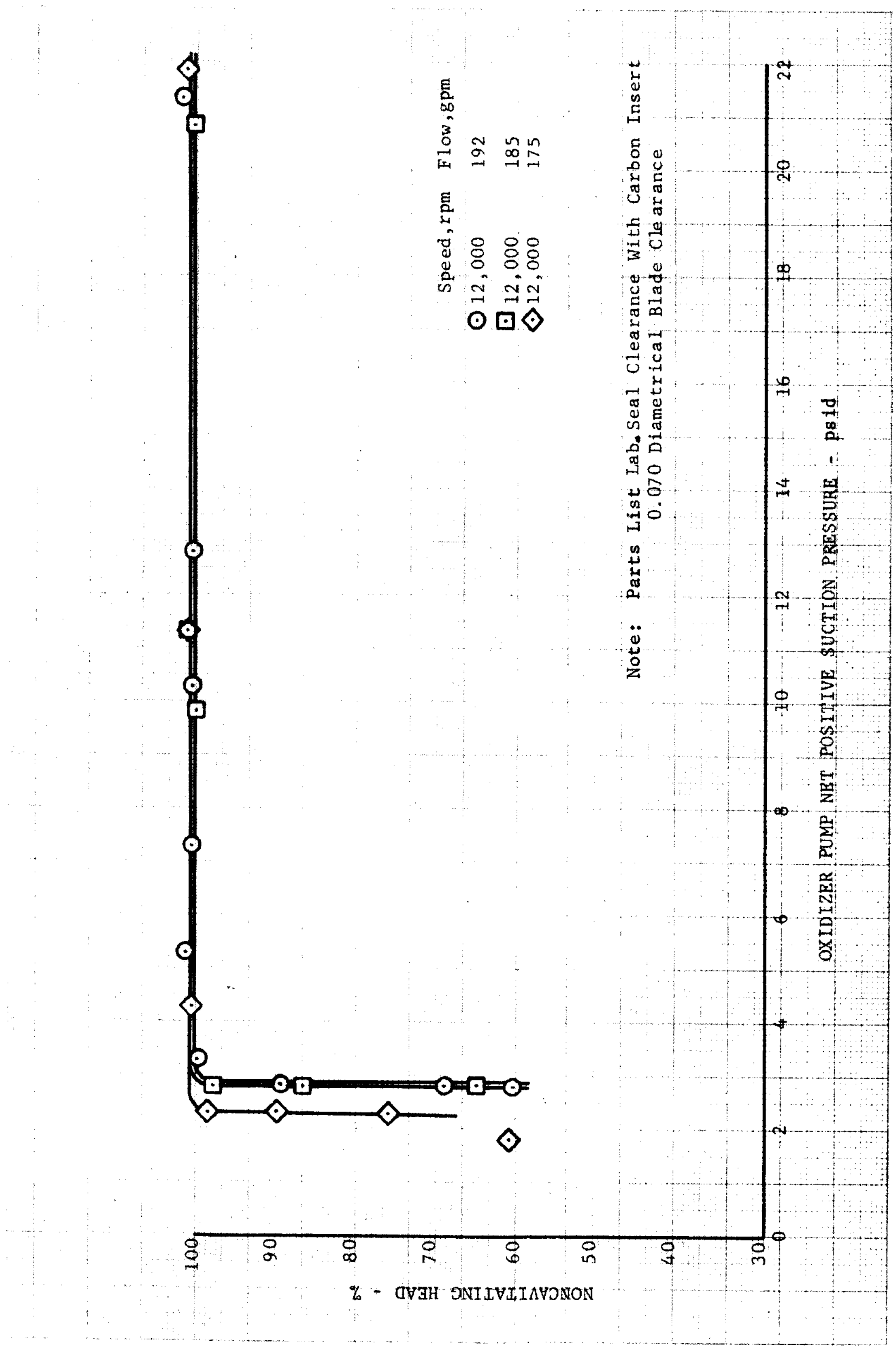


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Figure II-40. RL10A-3-3 Oxidizer Pump NPSP Performance (Rig B71C006-3)

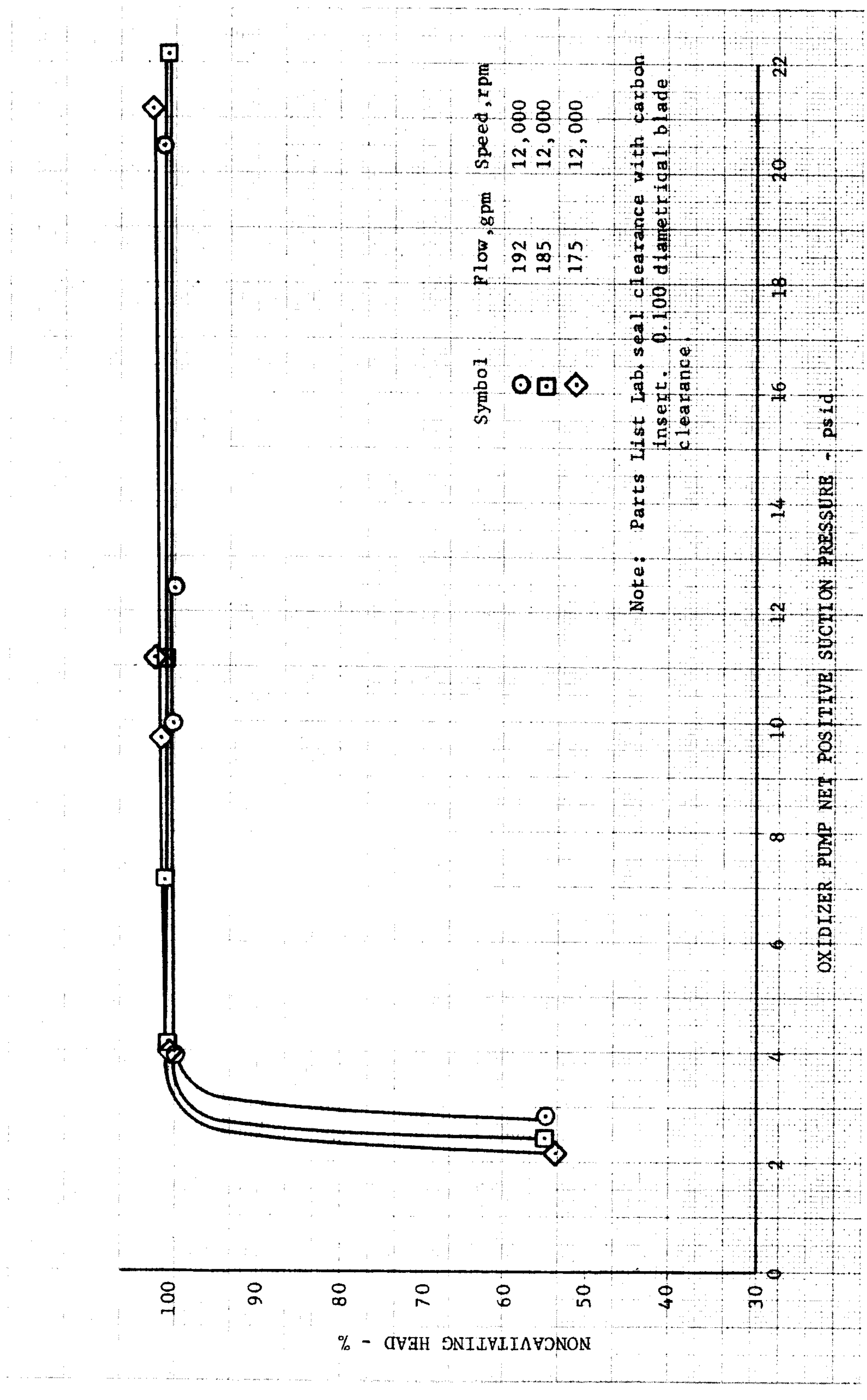

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Figure II-41. RL10A-3-3 Oxidizer Pump NPSP Performance (Rig B71C006-4)

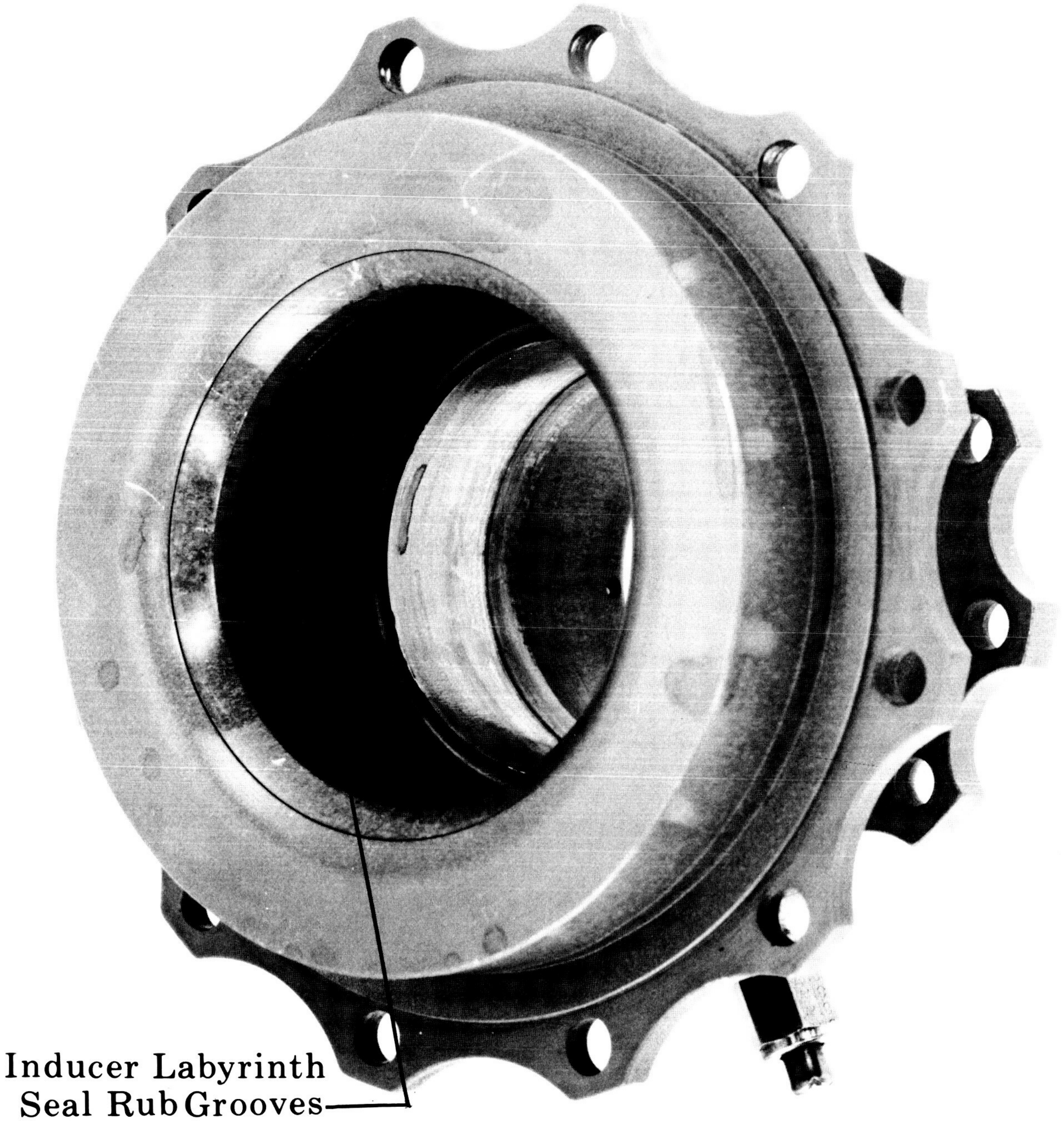


Figure II-42. RL10A-3-3 Oxidizer Pump Inducer Housing (Rig B71C006-4)   FD 18358

Testing continued with the labyrinth seal clearances increased to 0.022 in., rig B71C006, test 5, to determine the effect of wear and attendant increased clearance that could occur. Results presented in figure II-43 show that pump NPSP requirements were essentially unchanged. For the next test, rig B71C006, test 6, the inducer labyrinth seal shroud-to-inducer housing forward axial clearance was increased. The inducer housing in this area was originally contoured to direct the seal leakage flow back into the inducer inlet at a more favorable angle. This contour was eliminated when the forward inducer shroud-to-housing lip was removed to increase this clearance, slightly affecting the pump performance characteristics as indicated in figure II-44.

Evaluation of the performance results from the above test program established the following final oxidizer pump design configuration.

1. The original design 0.010-in. inducer labyrinth seal diametrical clearance was retained.

2. The inducer blade diametrical clearance was increased to 0.070 in.

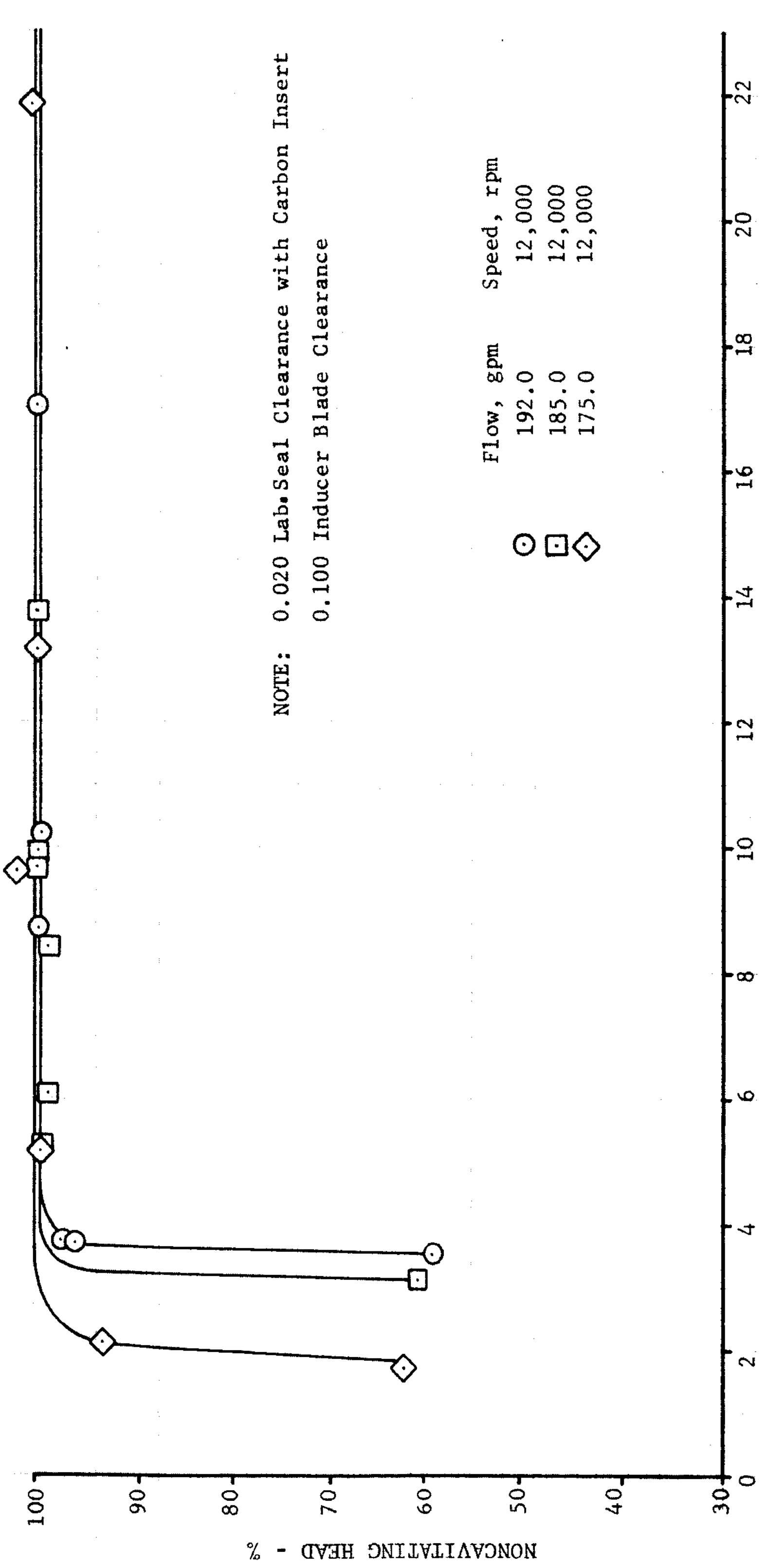
3. The inducer shroud-to-housing forward axial minimum clearance was increased to 0.066 in.

4. The impeller-to-housing forward axial minimum clearance was increased to 0.107 in.

Figure II-45 illustrates the original as compared to the final or current oxidizer pump parts list configuration. The new inducer and inducer housing design was subjected to a 10-hour endurance test on rig B71C006, tests 7 and 8. These tests were conducted with liquid oxygen, one hour at the 10% cavitation level and nine hours with normal engine inlet NPSP levels. Post-test inspection showed the parts to be in excellent condition with no inducer blade rub but with the usual labyrinth seal rubs (figure II-46).

In addition, several severe rub tests were completed on this configura-figuration to demonstrate satisfactory operation at extreme conditions reference rig B71C005, tests 2 and 3. Tests were performed with the pump operating at the 40% cavitation level. A 1000-lb load was applied to the thrust bearing support creating shaft deflections to 0.050 in. as measured at the inducer blade tip. Again, the post-test inspection showed a deep rub but otherwise the parts were in excellent condition.

The NPSP performance results from test 7 of rig B71C006 are presented in figure II-47. No appreciable change in the NPSP requirements is indicated as compared to the original oxidizer pump configuration represented in figure II-8. This design has been incorporated into the Parts List RL10A-3-3 oxidizer pump.



DF 20565

Figure II-43. RL10A-3-3 Oxidizer Pump NPSP Performance (Rig B71C006-5)

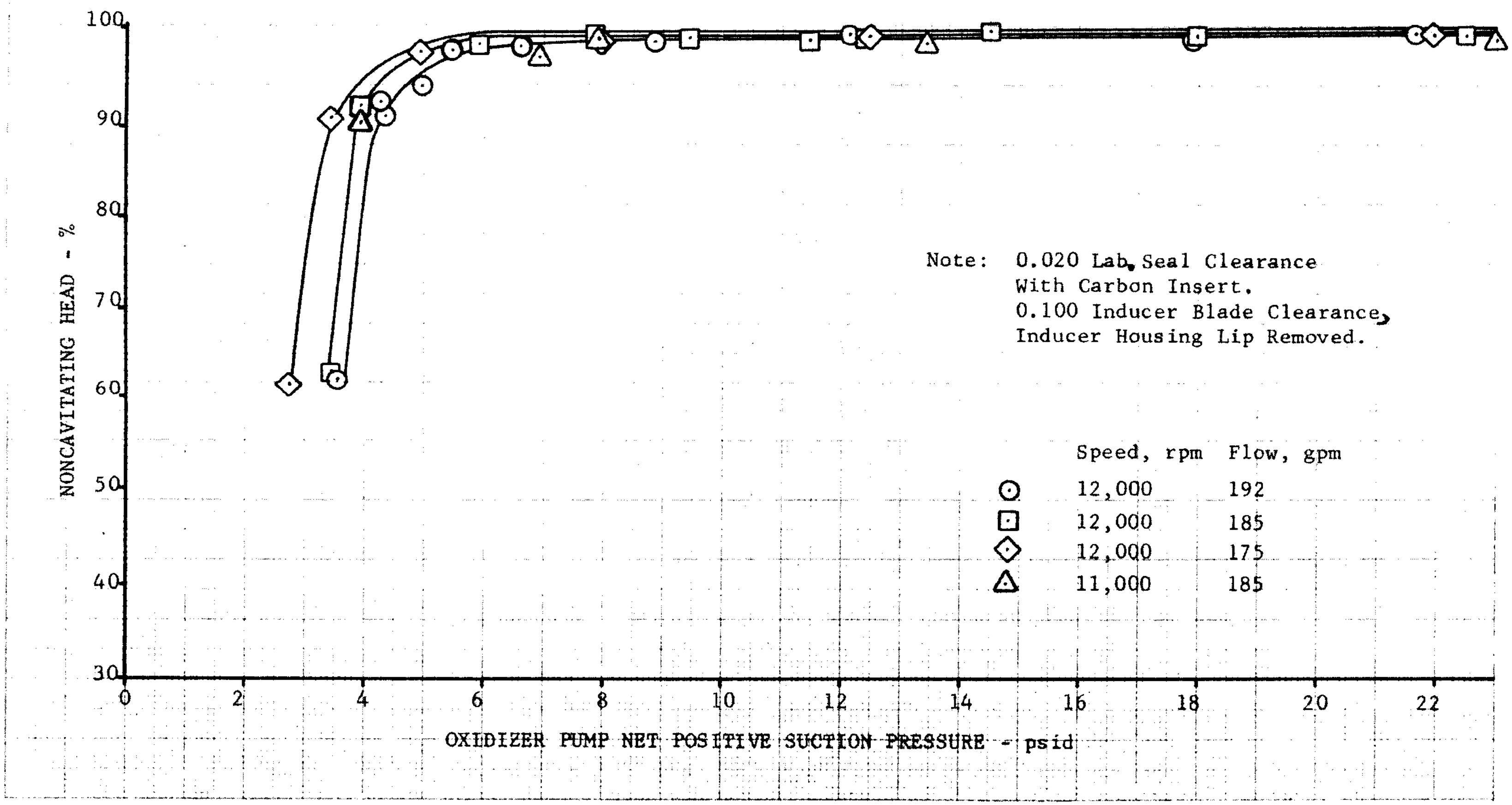


Figure II-44. RL10A-3-3 Oxidizer Pump NPSP Performance (Rig B71C006-6)

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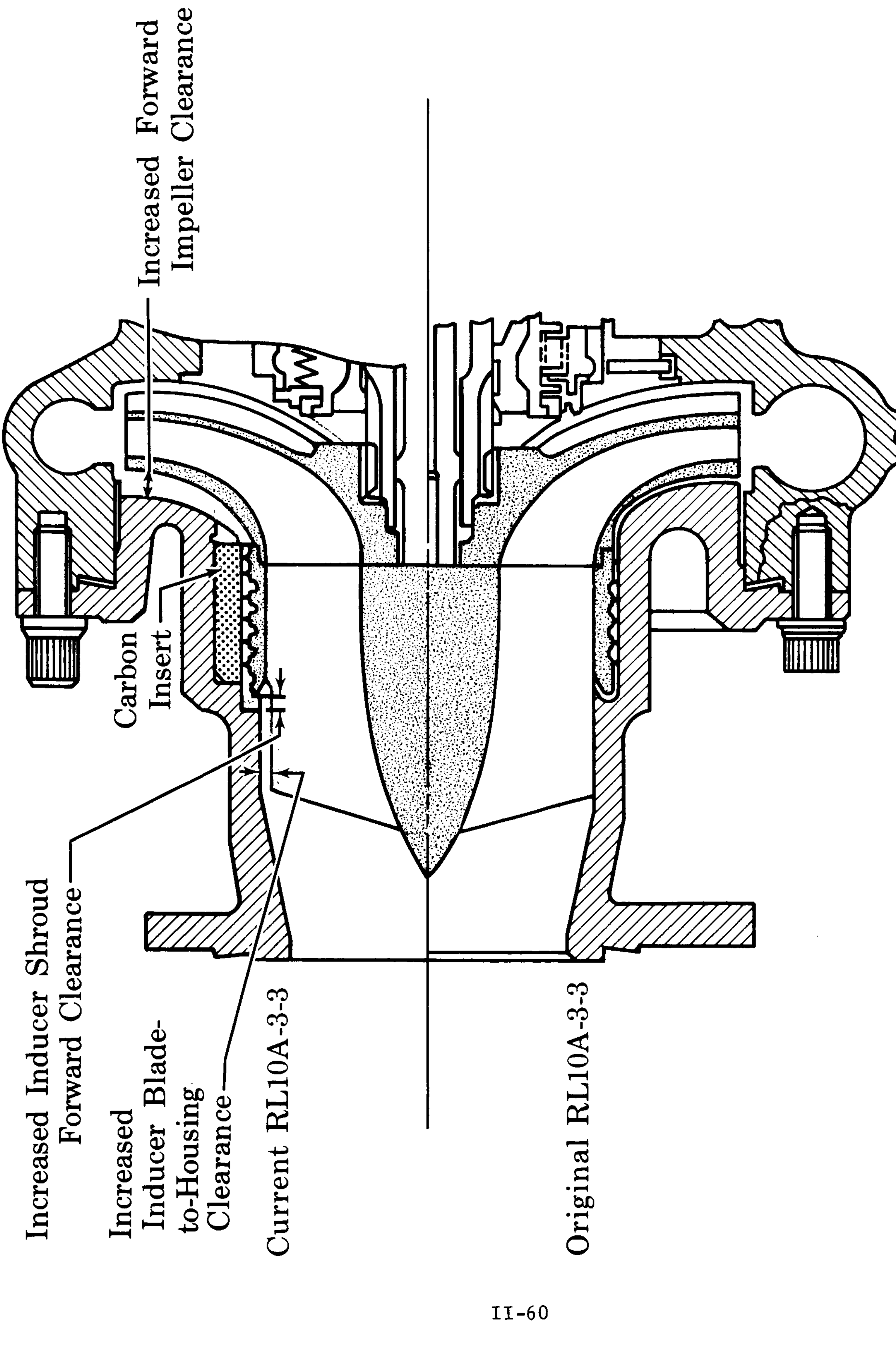

FD 18855

Figure II-45. RL10A-3-3 Oxidizer Pump Comparison

Figure II-46. RL10A-3-3 Oxidizer Pump Inducer Housing (Rig B71C006-8) FD 18352

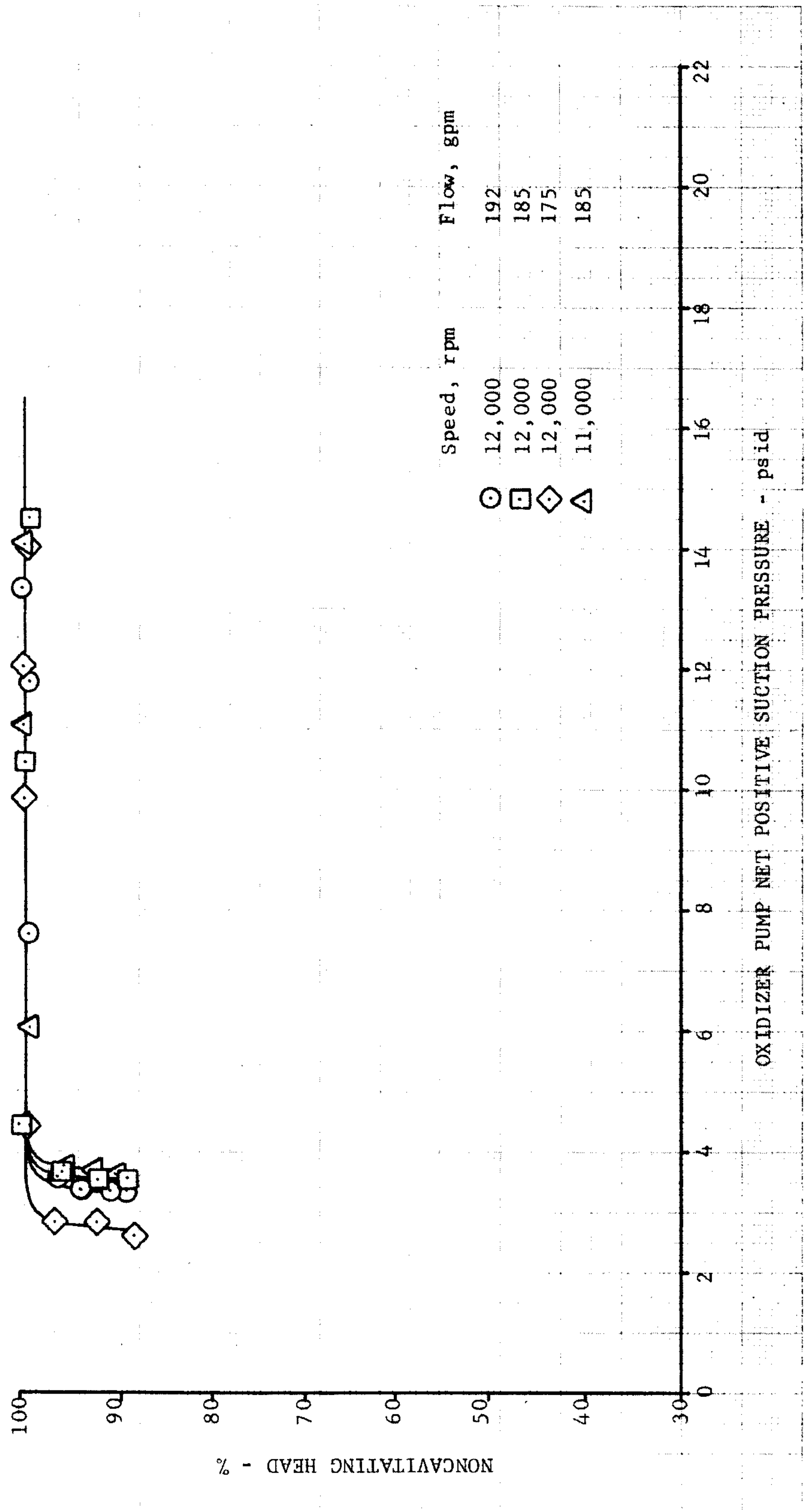

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Figure II-47. RL10A-3-3 Oxidizer Pump NPSP Performance (Rig B71C006-7)

SECTION III
CONCLUSIONS

1. The original RL10A-3-3 engine oxidizer pump design performed satisfactorily under extreme operating conditions that caused severe metal-to-metal inducer-to-housing rubbing.

2. Metal-to-metal rubbing in the RL10A-3-3 oxidizer pump was eliminated by incorporation of a carbon insert in the oxidizer pump inducer housing and increasing the inducer blade-to-housing clearance.

3. RL10A-3-3 oxidizer pump fires encountered during rig testing of non-Parts List pump configurations under conditions outside of Model Specification limits were caused by impeller-to-housing rubbing.

4. Increasing the impeller-to-housing axial clearance, increasing the inducer blade-to-housing diametrical clearance, and increasing the inducer shroud-to-housing axial clearance improved the capability of the RL10A-3-3 oxidizer pump to operate at conditions outside of Model Specification limits.

APPENDIX A
LIQUID OXYGEN RUBBING TESTS ON RL10 OXIDIZER PUMP MATERIALS

1. FOREWORD

This report describes the tests performed to determine the rubbing compatibility of various materials in liquid oxygen.

2. ABSTRACT

The standard method of determining liquid oxygen compatibility of a material is by impacting material immersed in liquid oxygen. However, the impact test does not give information concerning liquid oxygen compatibility in a rubbing condition. A special rub rig was constructed to evaluate the rubbing compatibility of various materials.

The rub rig tests were designed specifically to simulate possible rub conditions in the RL10 oxidizer pump at predetermined conditions of load, speed, pressure, and time. The test samples, with contact configurations of flat end, knife edge, round end, and pointed end, included those materials exposed to oxygen in the oxidizer pump.

All the materials used in the RL10 oxidizer pump were found compatible in liquid oxygen under the rub conditions tested. Twenty-four tests were made without a detonation or severe chemical reaction of the components.

3. TECHNICAL DISCUSSION

a. Method of Test

The rub rig installation on the liquid oxygen test stand is shown in figures A-1 and A-2. Cooling of the rub face was ensured by introducing liquid oxygen flow into the rig center and discharging at two locations around the periphery. The sample port position allowed specimen changes without removal of the rig from the test stand. Power to drive the rig shaft was provided by a variable drive motor through a 4:1 pulley system. Accelerometers were mounted for continuous vibration monitoring during the tests.

FD 18356

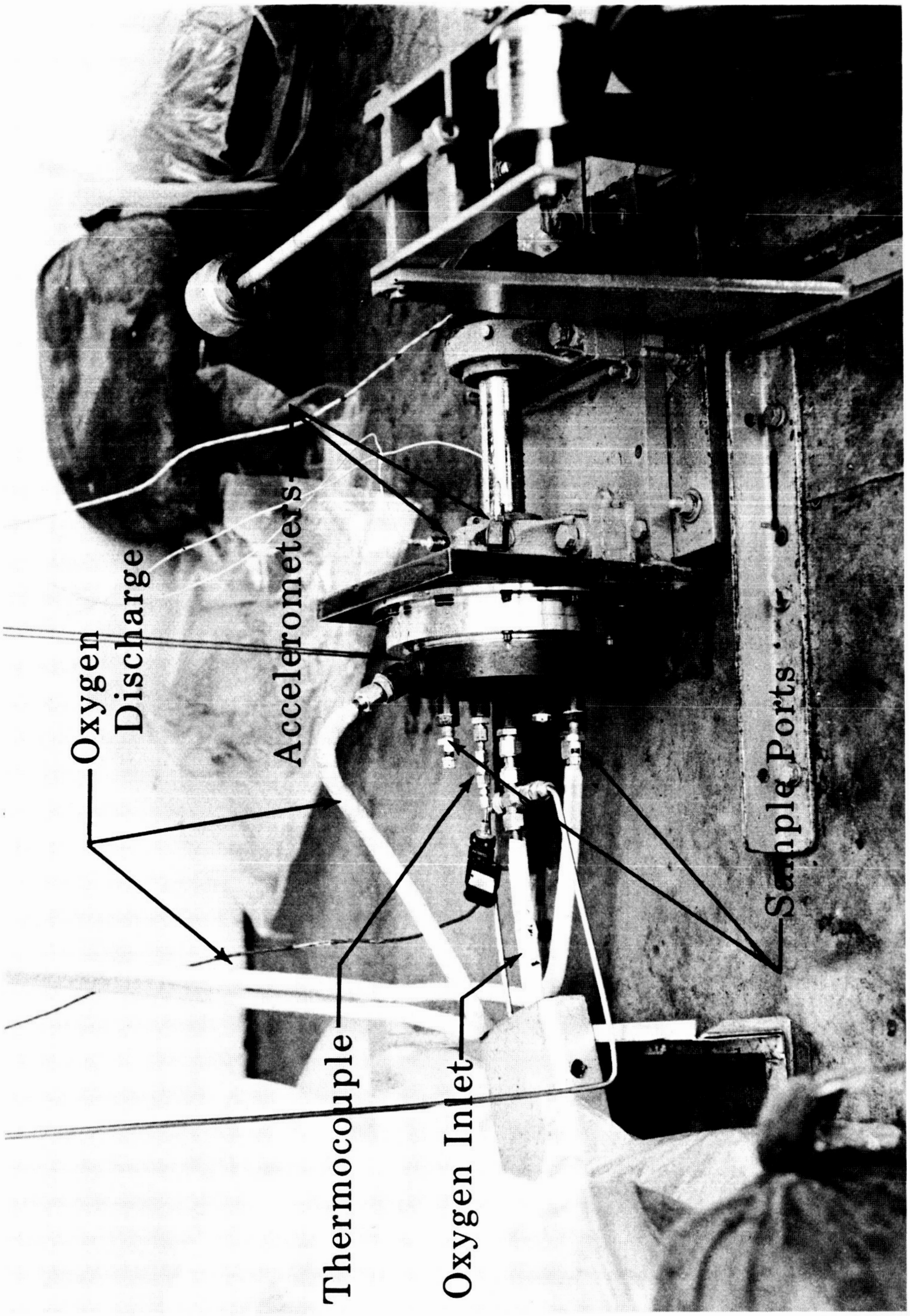

Figure A-1. Oxidizer Rub Rig

FC 8828

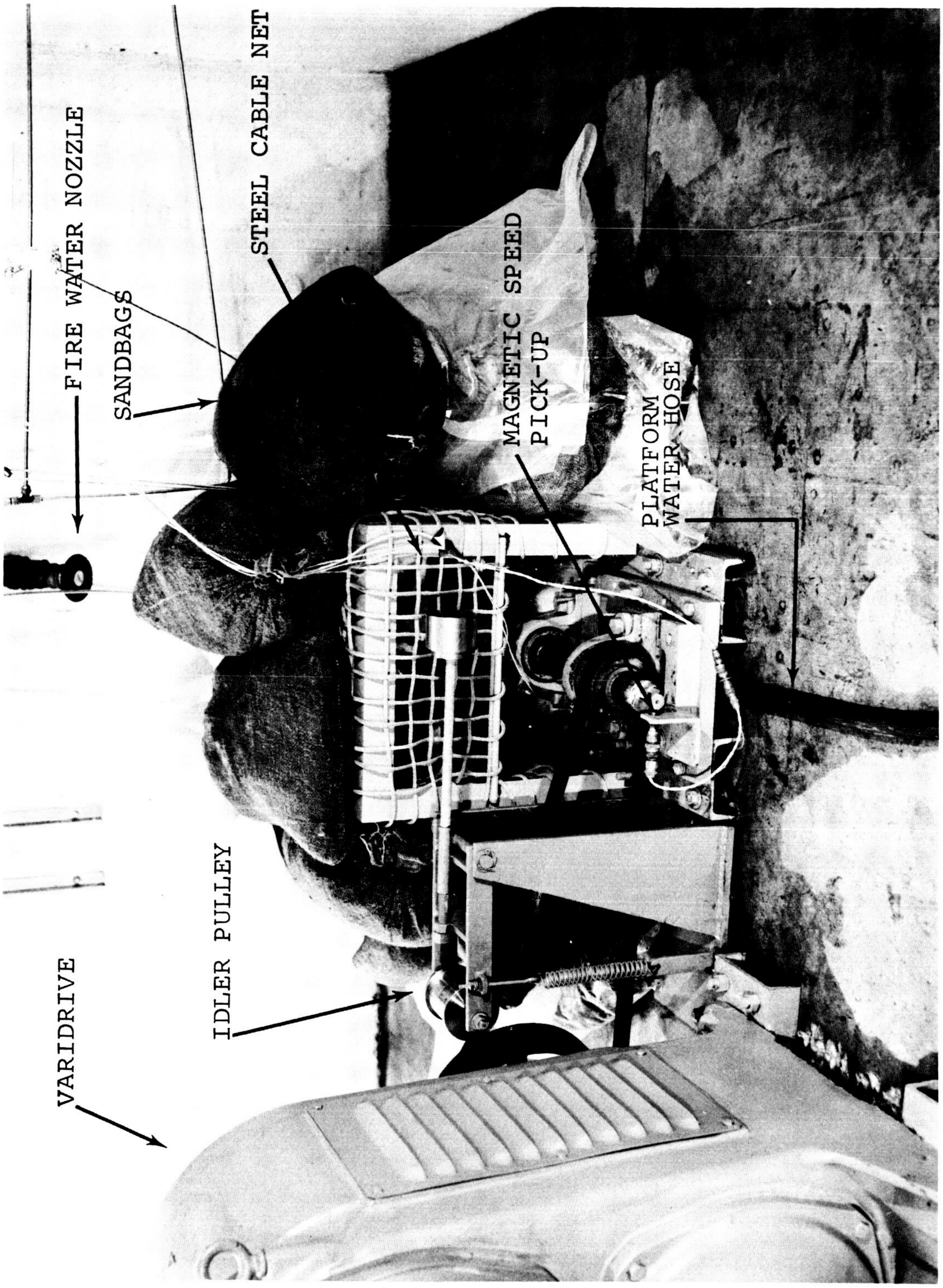

Figure A-2. Rear View of Oxidizer Rub Rig

The rub face was rotated at speeds from 3600 to 8000 rpm (92-204 fps) while flowing liquid oxygen through the rig at pressures of 60-70 psig. Specimen exposure time at these conditions was 50 to 300 seconds.

b. Samples

The rubbing condition of the materials tested was obtained by pressing three cylindrical, spring-loaded specimen pins against the side of a 6.5-in. OD rub face. Four pin configurations were used as illustrated in figure A-3, with the pin load limited to one pound for all tests. Pin and rub face materials were AMS 4130 aluminum alloy, AMS 5646 stainless steel, AMS 4650 copper-beryllium alloy, and AMS 5646 stainless steel chrome plated per AMS 2406. In addition, pins were made from Purebon 5Ag carbon and National TS-282 carbon. Wear analysis of the pins was made by measurements of weight and reduction in length.

c. Analysis of Results

The materials tested and results are presented in table A-1. Twenty-four tests were made without a detonation or severe chemical reaction of the specimens. Typical wear patterns from AMS 5646 pin and rub face combination are shown in figures A-4 through A-8. Where noticeable wear was evident on the metal pins, black oxides were found on the rub faces. The carbon pins wore less than corresponding metal pins (test 20), but were more susceptible to breakage.

4. CONCLUSIONS

The materials used in the RL10 oxidizer pump were found compatible in liquid oxygen under the rub conditions tested. The carbon material, on the compatibility threshold by impact tests, was found compatible by the rub method.

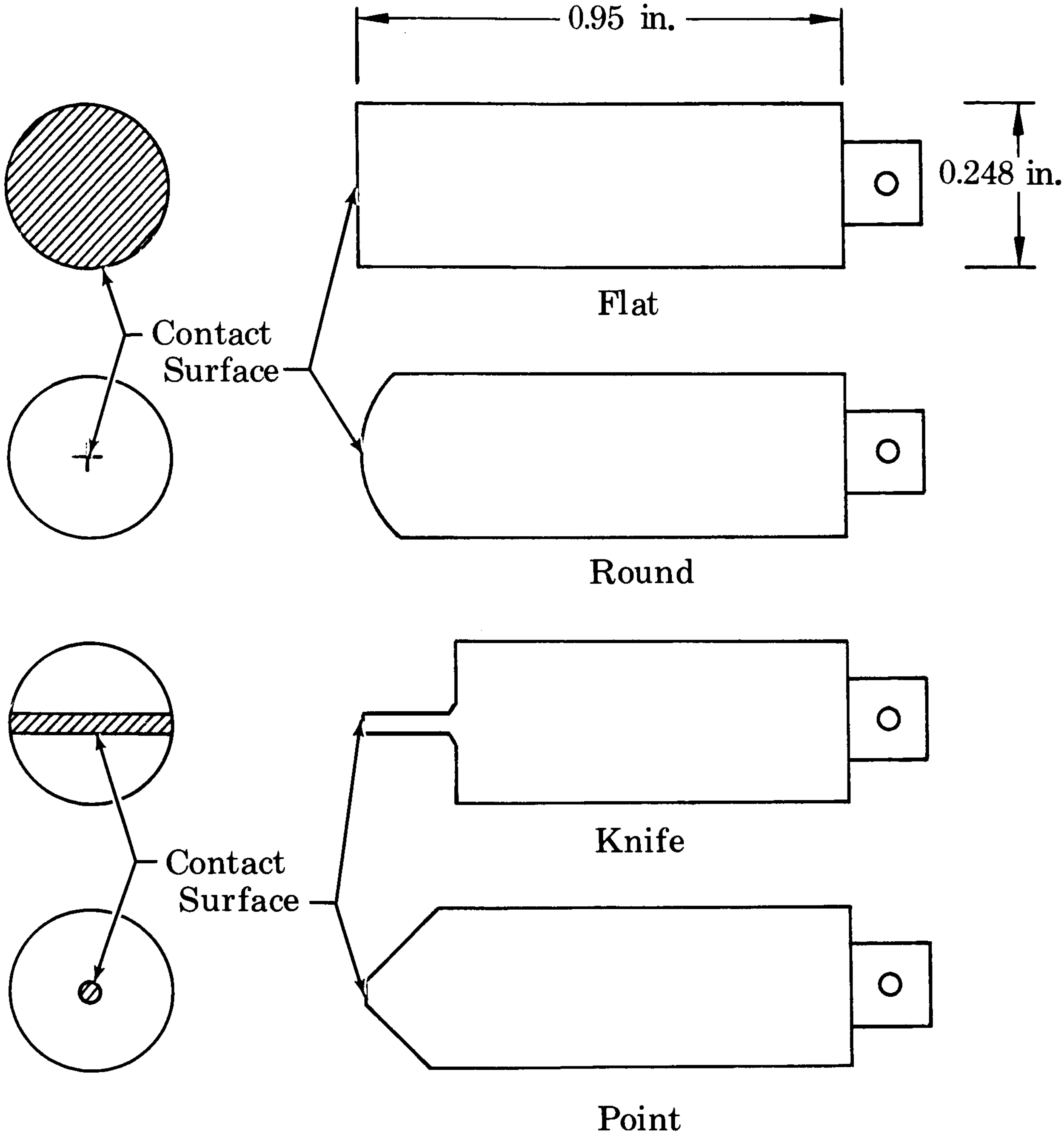

Figure A-3. Test Specimen Pin Configurations FD 18344

Table A-1. Liquid Oxygen Rub Test Results

Test No.	Material	Rubbing Time, sec	RPM	Rubbing Ring Velocity, fps	Oxidizer Inlet Pressure, psig	Change in Weight of Pins, gm	Change in Length of Pins, in.	Pin Configuration	Comments
1	AMS 5646 Pins, AMS 5646 Ring	50	8000	204	70	-0.0042 -0.0068 -0.0059	-0.006 -0.007 -0.007	Round	Marks were noticed on rings where pins had been tightened down on them.
2	AMS 5646 Pins, AMS 5646 Ring	60 60	3600 5000	92 128	60	-0.012 -0.010 -0.012	-0.0263 -0.0230 -0.0249	Point	Small "burn" or heat marks on ring.
3	AMS 5646 Pins, AMS 5646 Ring	180	5000	128	60		-0.0027 -0.0213 -0.0221	Point	Pins were not weighed before run. One pin had considerably less wear than others.
4	AMS 5646 Pins, AMS 5646 Ring	60	5000	128	60	-0.0021 -0.0060 -0.0008	-0.0047 -0.0153 +0.0003	Knife	One pin had less wear than others.
5	AMS 5646 Pins, AMS 5646 Ring	300	5000	128	60	-0.0009 -0.0017 -0.0008	-0.0004 ±0.0000 +0.0001	Flat	Ring had ±0.0002 - 0.0010 in. gall marks. Pins galled.
6	AMS 5646 Pins, AMS 5646 Ring	60	8000	204	60	-0.0079 -0.0069 -0.0096	-0.0208 -0.0174 -0.0236	Knife	One knife edge bent slightly.
7	AMS 5646 Pins, AMS 5646 Ring	60	8000 5000	204 128	60	-0.0147 -0.0174 -0.0135	-0.0099 -0.0108 -0.0093	Round	Speed was accidentally started at 8000 rpm and brought down to 5000 over a 60-sec period.
8	AMS 5646 Pins, AMS 5646 Ring	60	5000	128	60	N.R.*	N.R.*	Flat	Pins were not weighed or measured before run.

Table A-1. Liquid Oxygen Rub Test Results (Continued)

Test No.	Material	Rubbing Time, sec	RPM	Rubbing Ring Velocity, fps	Oxidizer Inlet Pressure, psig	Change in Weight of Pins, gm	Change in Length of Pins, in.	Pin Configuration	Comments
9	AMS 4130 Pins, AMS 5646 Ring	60	8000	204	60	+0.0003 +0.0002 +0.0002	+0.0004 ±0.0000 +0.0009	Flat	Black deposit noticed on both ring and pins.
10	AMS 4130 Pins, AMS 5646 Ring	60	8000	204	60	-0.0035 -0.0067 -0.0064	-0.0489 -0.0558 -0.0550	Knife	Knife edge bent and material curled over knife edge.
11	AMS 4130 Pins, AMS 4130 Ring	60	8000	204	60	±0.0000 +0.0020 -0.0021	+0.0032 +0.0066 +0.0056	Flat	Some material imbedded on tip of specimens.
12	AMS 4130 Pins, AMS 4130 Ring	60	8000	204	60	-0.0014 ±0.0000 -0.0065	-0.0442 ±0.0000 -0.0471	Knife	Material curled over knife edge.
13	AMS 4650 Pins, AMS 5646 Ring	60	8000	204	60	-0.0005 +0.0005 -0.0011	±0.0000 ±0.0000 +0.0004	Flat	Hardly any wear evident.
14	AMS 4650 Pins, chrome plated**, AMS 5646 Ring	60	8000	204	60	-0.0029 -0.0001 -0.0039	-0.0002 -0.0005 -0.0006	Flat	Little wear evident.
15	Chrome plated** AMS 5646 Pins, AMS 4650 Ring	60	8000	204	60	-0.0004 -0.0002 -0.0002	-0.0007 +0.0005 +0.0003	Flat	Pin rub faces were copper colored from AMS 4650 ring.
16	AMS 5646 Pins, AMS 4650 Ring	60	8000	204	60	-0.0085 -0.0055 -0.0062	-0.0463 -0.0423 -0.0446	Knife	Metal curled over knife edge.
17	Chrome plated** AMS 5646 Pins, AMS 4650 Ring	60	8000	204	60	-0.0005 -0.0008 -0.0009	-0.0013 -0.0028 -0.0043	Knife	Little wear evident.

Table A-1. Liquid Oxygen Rub Test Results (Continued)

Test No.	Material	Rubbing Time, sec	RPM	Rubbing Ring Velocity, fps	Oxidizer Inlet Pressure, psig	Change in Weight of Pins, gm	Change in Length of Pins, in.	Pin Configuration	Comments
18	AMS 4650 Pins, chrome plated** AMS 5646 Ring	120	8000	204	60	-0.0040 -0.0229 -0.0206	+0.0136 -0.0552 -0.0537	Knife	Run as planned.
19	AMS 5646 Pins, AMS 4650 Ring	60	8000	204	60	-0.0022 -0.0017 -0.0043	-0.0011 -0.0006 -0.0003	Flat	Run as planned.
20	Purebon 5Ag carbon pin, chrome plated** AMS 5646 Ring	60	8000	204	60	N.R.*	N.R.*	Flat	Only wear evident was a very slight slurred area on the edge of one pin rub face. Pins not weighed or measured.
21	TS-282 carbon pins, chrome plated** AMS 5646 Ring	N.R.*	N.R.*	N.R.*	N.R.*	N.R.*	N.R.*	Flat	Pins broke during installation.
22	Purebon 5Ag carbon pins, chrome plated** AMS 5646 Ring	300	8000	204	60	N.R.*	N.R.*	Round	Pins not weighed or measured. Hardly any wear evident.
23	TS-282 carbon pins, chrome plated** AMS 5646 Ring	120	8000	204	60	N.R.*	N.R.*	Knife	Pins broke at knife edge, some wear evident on the end of one broken pin.
24	Purebon 5Ag carbon pins, chrome plated** AMS 5646 Ring	120	5000	128	60	N.R.*	N.R.*	Knife	Knife edges broke off. Evidently pins did not contact ring after fracture.

*N.R. - No Run. See comments.
**Per AMS 2406

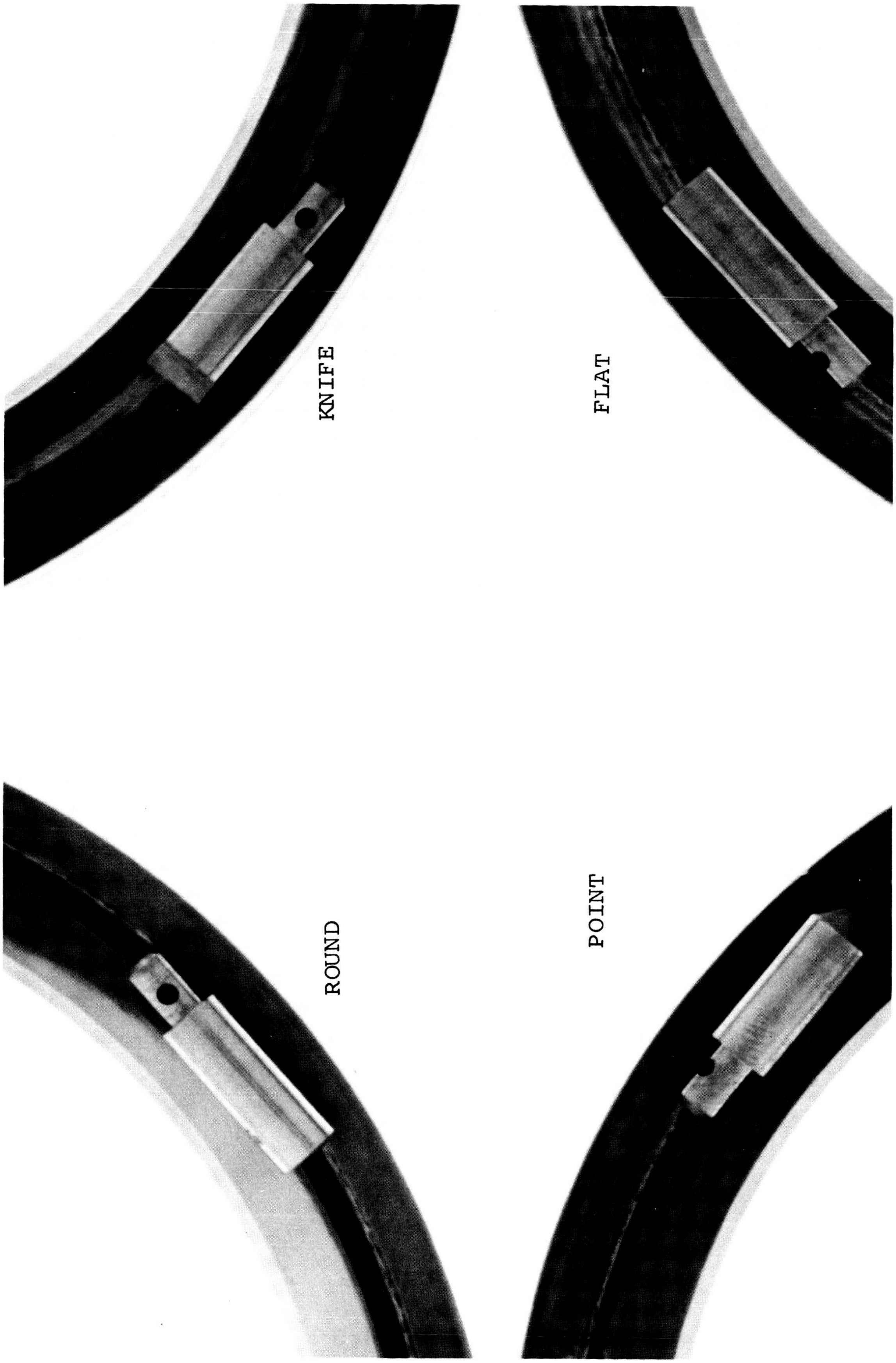

Figure A-4. Wear Tracks of AMS 5646 Pins on AMS 5646 Rings

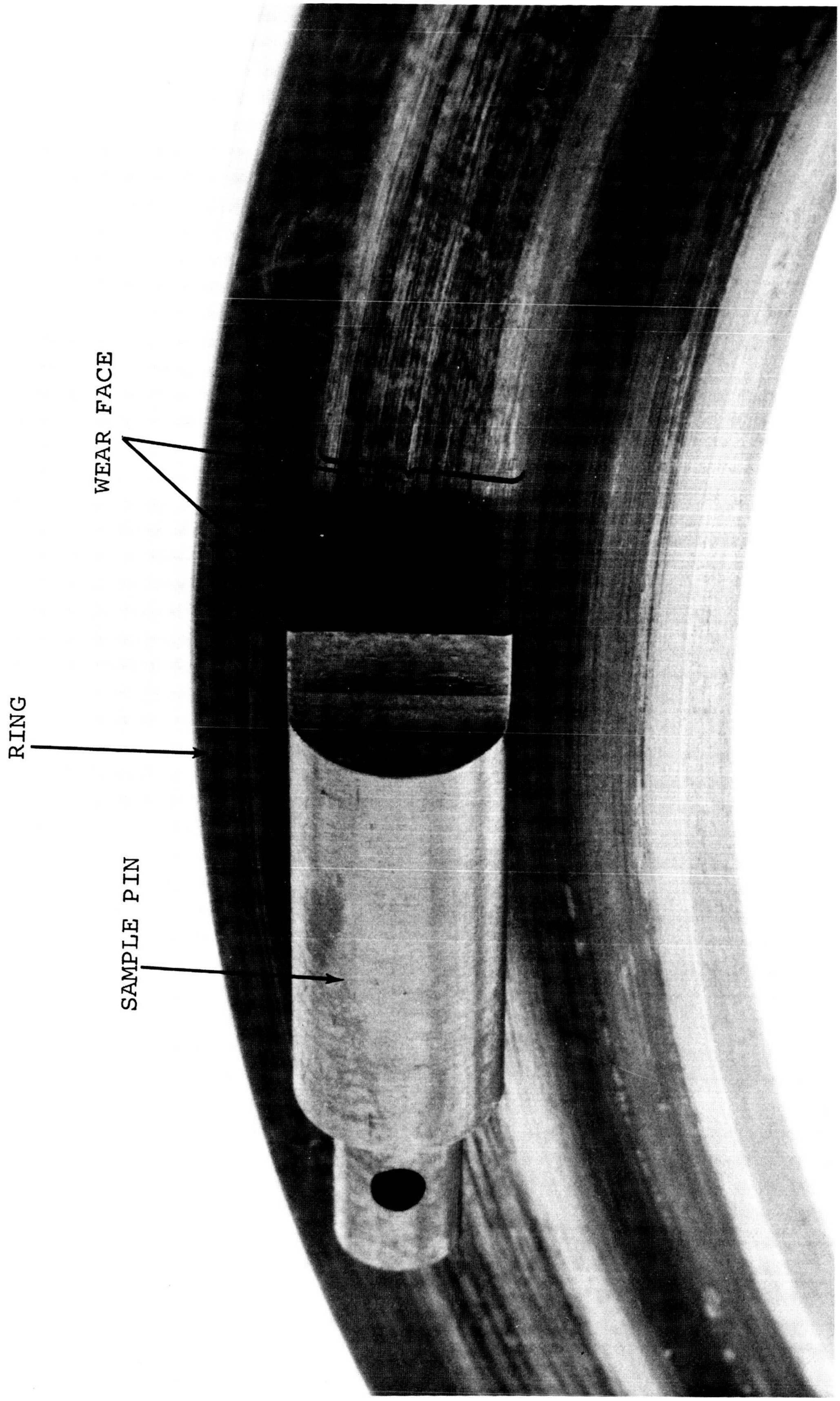

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Figure A-5. Wear Track of AMS 5646 Knife Edge Pin on AMS 5646 Ring

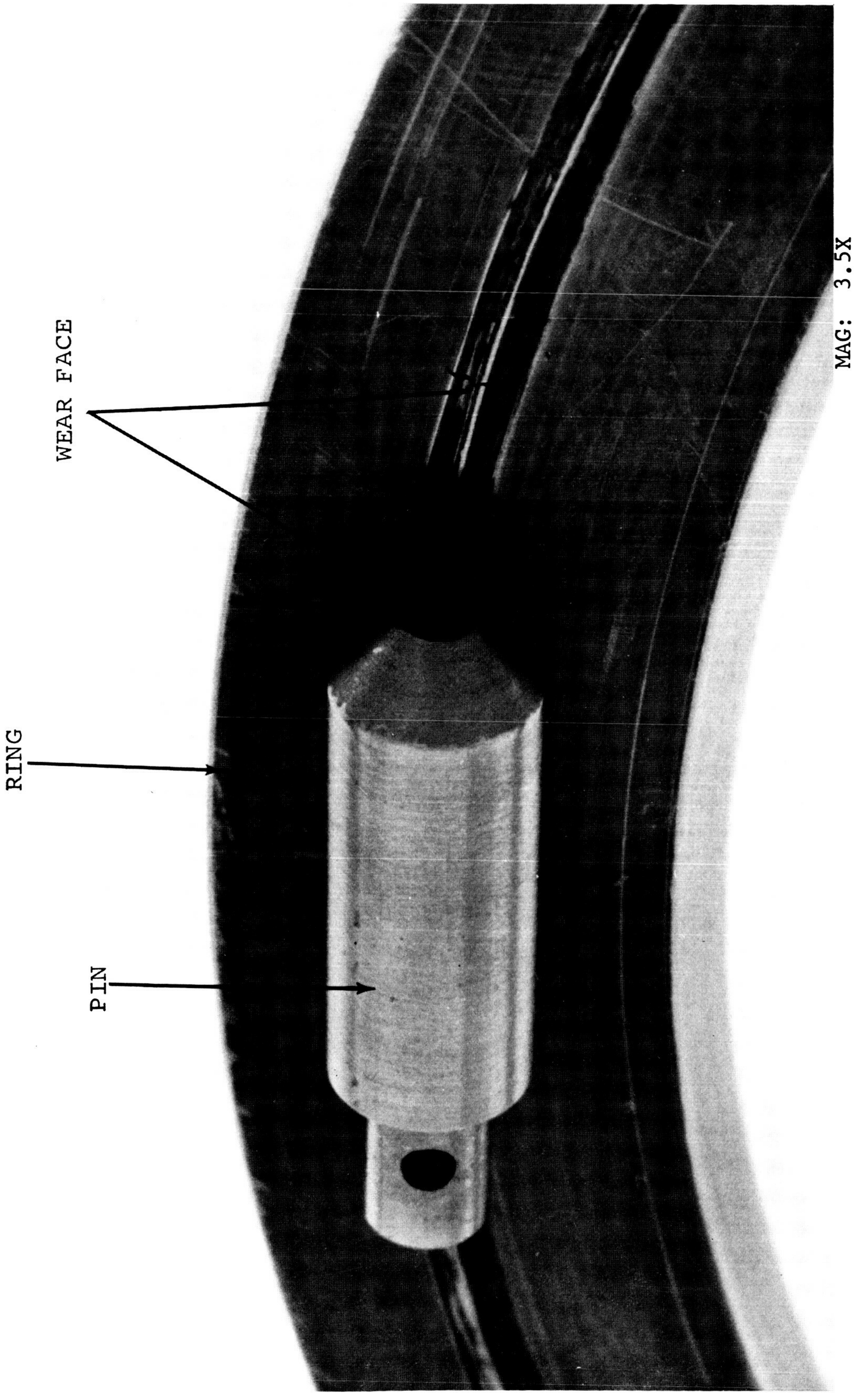

Figure A-6. Wear Track of AMS 5646 Point Shaped Pin on AMS 5646 Ring

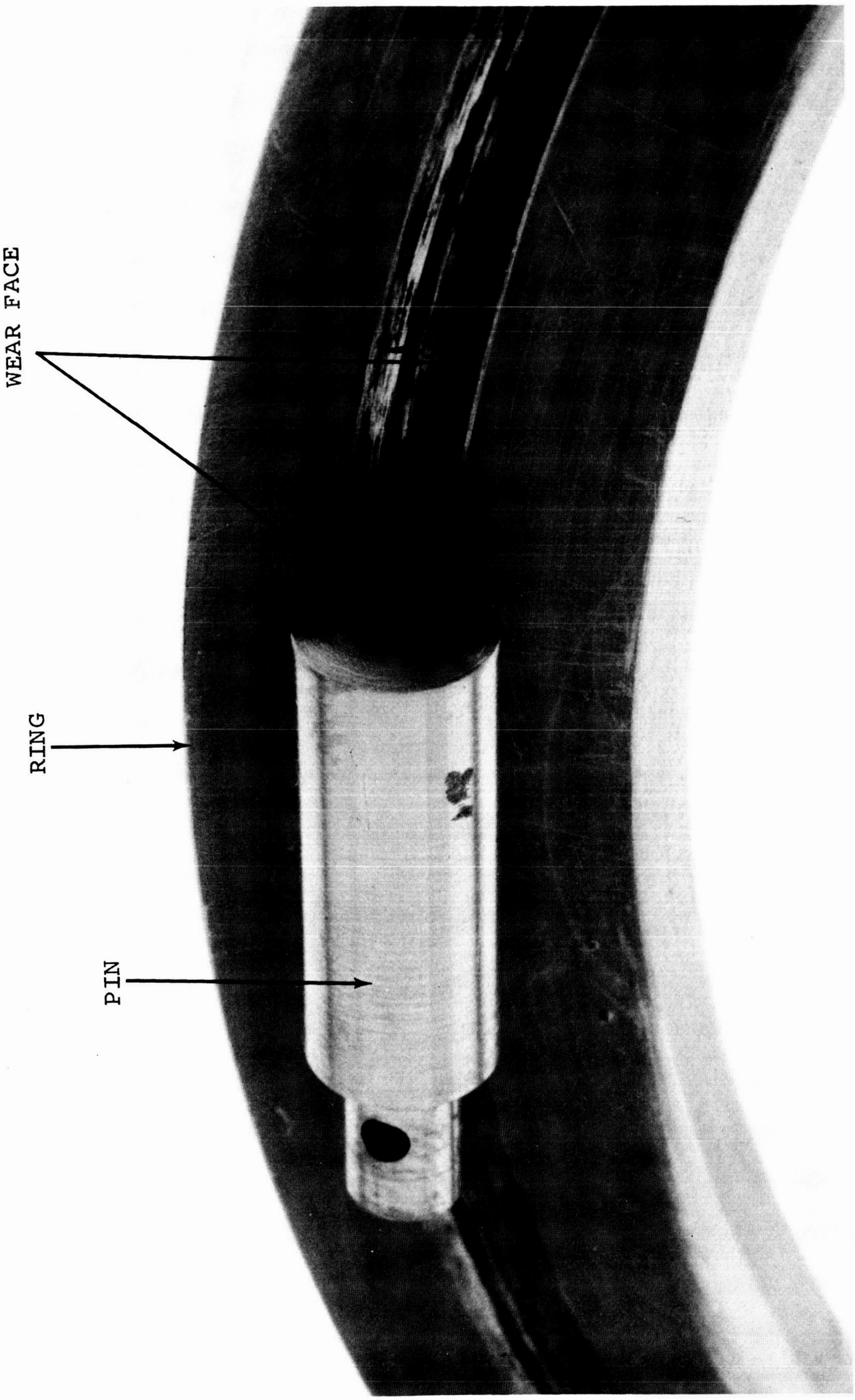

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Figure A-7. Wear Track of AMS 5646 Round Headed Pin on AMS 5646 Ring

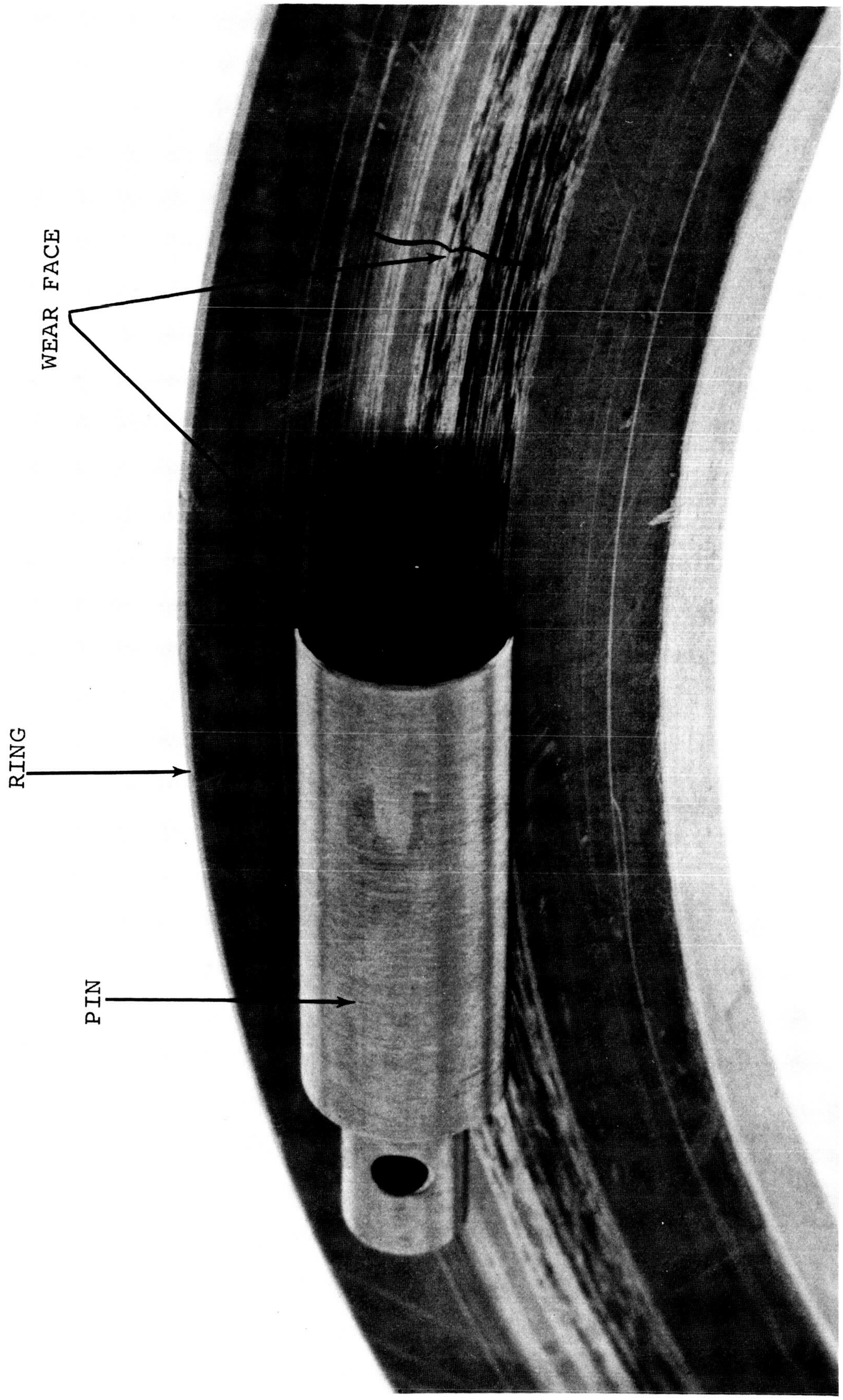

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Figure A-8. Wear Track of AMS 5646 Flat Headed Pin on AMS 5646 Ring